Supplementary Information for manuscript "A systems approach reveals urban pollinator hotspots and conservation opportunities" by Baldock et al.

Contents

Supplementary Methods

1. Creating land use maps for Bristol, Reading, Leeds and Edinburgh

1.1. Selecting urban study areas for each city

The 'urban area' of each city was downloaded in Shapefile format from the UK Data Service[1,2]. The Office for National Statistics[3] definition of an urban area in England and Wales is an area with 10,000 people or more; in Scotland this is 3,000 people or more. For each of the study cities these data were overlain on an OS Mastermap in ArcGIS version 10, and the relevant polygons covering each cities 'urban area' were selected. The urban study areas were created based upon the relative size, continuous nature of the urban area and it being surrounded by non-urban land uses. For example the 'Greater Yorkshire urban area' was reduced to areas covering Leeds only and not satellite towns and cities, while parts of Wokingham was included within the Reading urban area as Wokingham and Reading form a continuous urban entity. Adjacent urban greenspaces (e.g. golf courses) and new urban developments not present when the 2001 data were created were identified using Google Earth and the 'urban area' for each city edited to include these. The final 'urban areas' for each city were aggregated together to form one polygon for each city using the dissolve function in ArcGIS 10.

1.2. Mapping land uses

Land use data were extracted from multiple sources (Table A) and combined to create a land use map for each city. Mastermap data[4] were downloaded for the 'urban areas' of all study cities. The following land uses were extracted using ArcMap 10: buildings, inland water, other manmade surface, other natural surface, pavement, private gardens, railway-manmade, railway-natural, road verges and roundabouts, roads, tidal water and foreshore. Data on the location of allotments, parks, and cemeteries, churchyards and burial grounds (hereafter termed 'cemeteries') was provided by local councils[5-9] and ground-truthed by project staff. Data on the location of nature reserves (defined in this study as Local Nature Reserves (LNRs) or Sites of Special Scientific Interest (SSSIs)) within the urban areas were downloaded[10-11]. Information obtained from ground-truthing and mapping carried out by project staff was also incorporated, for example private allotments not in council databases were identified using Google Earth and added to the land use maps.

The Mastermap, park, allotment, cemetery and nature reserve data were combined to create a land use map for each city. Nature reserves data took precedence over all other land uses (i.e. if a location was both a ‘park’ and a ‘nature reserve’ it was assigned as a ‘nature reserve’. Park, allotment and cemetery land covers took precedence over other Mastermap categories. All of the above Mastermap categories were included in the creation of a land use map, however land uses such as railways, roads and tidal areas were considered unsafe for the field teams to sample. Nine land uses were selected for sampling: nature reserves, allotments, parks, cemeteries (including churchyards and burial grounds), private gardens (hereafter ‘gardens’), other natural surface (hereafter ‘other greenspace’), road verges and roundabouts (hereafter ‘verges’), pavement and other manmade surface (hereafter ‘manmade surface’). These land uses are defined in Supplementary Table 2.

Railway verges (defined as ‘railway-natural’ in Mastermap) were not sampled as access could not be granted for safety reasons. Roads, railway tracks and water were not sampled for safety reasons but are also unlikely to contain many flowers. Buildings are unlikely to have many flowers. Although green roofs and walls on buildings can provide flowers, these were very limited in area in the four study cities (personal observation). Furthermore there are no data sets available that map locations of green walls and roofs in the four cities so they could not be incorporated into the land use maps.

Table A. Data sets used to create land use maps for Bristol, Reading, Leeds and Edinburgh

Data Description	Source	Reference number
English Urban Areas 2001	UK Data Service (2001)	1
Scottish Settlements 2001	General Register Office for Scotland (2001)	2
Mastermap data (05/01/2012 upload)	Ordnance Survey (2012)	4
Bristol greenspace data	Bristol City Council (2012)	5
Edinburgh allotments/cemeteries data	Edinburgh City Council (2012)	6
Leeds greenspace data	Leeds City Council (2012)	7
Reading allotments shapefile (Jan 2012)	Reading Council (2012)	8
Wokingham allotments shapefile data	Wokingham Borough Council (2012)	9
English Nature Reserves (SPA, SAC, SSSI, LNR, Ramsar, NNR)	Natural England (2011)	10
Scottish Nature Reserves (SPA, SAC, SSSI, LNR, Ramsar, NNR)	Scottish Natural Heritage (2011)	11

2. Selecting garden sites for sampling

Since very few private gardens were large enough to contain a 100 m transect, sampling was split among ten gardens in each region (each containing a 10 m transect length). All ten gardens per region were located within a single Output Area (OA). OAs are the lowest geographic level at which census estimates are provided and are typically classified based on tenure and dwelling type with a target size of 125 households[12]. Boundary data for all OAs in each city were downloaded from Edina[13,14] and associated data on the number of households in each OA was downloaded from CASWEB[15]. OAs were selected using stratified random sampling to capture variation in garden size and management across a gradient of median household income based on the procedure described below.

The finest scale at which median household income data are available in England is the Lower Layer Super Output Area (LSOA). LSOAs are an aggregation of adjacent OAs with similar social characteristics and typically contain 4 to 6 OAs with a population of around 1500. In Scotland, the equivalent census unit to the LSOA is the Data Zone (DZ) and is an aggregation of output areas with a typical population of between 500 and 1,000 household residents. Median household income data from 2010 (defined as the income of a given household where half of the homes in the area earn more and half earn less) for each LSOA (DZ in Edinburgh) per city was downloaded from Experian[16] and used to create five income bands per city whereby 20% of LSOA/DZs per city were assigned to each income band (see Table B). Ten LSOAs/DZs were randomly selected for each city (one per region) with the constraint that there were two LSOA/DZs per income band in each city (Fig. A). In order not to confound socio-economic influences with geographic effects, LSOA/DZs assigned the same income band were not located in adjacent regions (Fig. A). Within each selected LSOA/DZ an OA was randomly chosen with the constraint that selected OAs contained at least 80 residential addresses and the majority of gardens were $\geq 30\ m^2$. Scottish OAs contain fewer households than English OAs and therefore two adjacent OAs were selected for each region in Edinburgh. See Fig. A for an example of how LSOAs and OAs were chosen within a city. The range of median household income of LSOAs/DZs for each income band for each city is shown in Table B. The median household income for selected LSOAs/DZs is shown in Table C.

All households within selected OAs (89–252 households per OA) were asked for permission to sample their back garden and ten gardens for which access permission was granted were selected at random for sampling. Every effort was made to sample the same ten gardens in each sampling round. If a garden could not be accessed in all sampling rounds, alternative gardens in the same OA were selected to ensure ten gardens were sampled each time.

Figure A. The ten regions in Leeds and an illustration of how garden sites were selected

Each region (formed of adjacent electoral census wards grouped together) is shown in a different colour. One lower super output area (LSOA; data zones (DZ) in Edinburgh) was randomly selected in each region and one output area (OA; two in Edinburgh due to smaller size) then selected within each LSOA following the approach described in Supplementary Methods Part 2. Sampled gardens were located within selected OAs. Note that the selection procedure ensured that adjacent regions did not contain sampled OAs belonging to the same income band (n=5 per city, see Table B for income band categories).

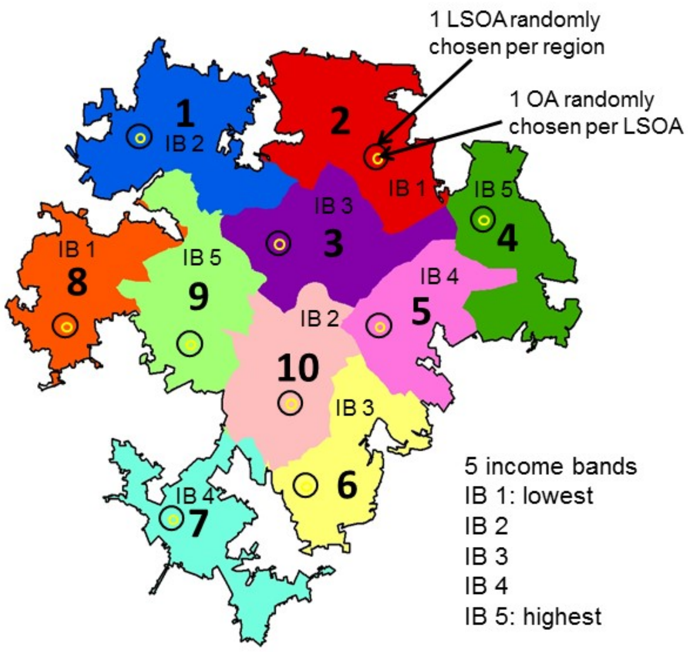


Table B. The range of median household income (£) of LSOAs and DZs for each income band per city

Income band	Bristol	Reading	Leeds	Edinburgh
1	9193.000000 – 21942.5	16040.500000 – 27684	6834.000000 – 19053.5	9719.000000 – 21770.0
2	21942.500001 – 25535.0	27684.000001 – 33108	19053.500001 – 22074.0	21770.000001 – 27640.0
3	25535.000001 – 29361.5	33108.000001 – 37129	22074.000001 – 26698.5	27640.000001 – 34923.5
4	29361.500001 – 35807.0	37129.000001 – 44023	26698.500001 – 33139.5	34923.500001 – 42769.0
5	35807.000001 – 56128.0	44023.000001 – 58129	33139.500001 – 53045.5	42769.000001 – 73833.0

Table C. Characteristics of LSOAs/DZs and OAs used for garden sampling in each city

City	Region	LSOA/ DZ code	Median household income (£)	LSOA income band	OA code	No. of households per OA
Bristol	1	E01014641	33,420.0	4	00HBPK0027	134
Bristol	2	E01014690	21,215.0	1	00HBPS0009	105
Bristol	3	E01014637	28,676.5	3	00HBPJ0003	116
Bristol	4	E01014622	25,184.0	2	00HBPH0040	105
Bristol	5	E01014900	32,608.0	4	00HDPD0032	139
Bristol	6	E01014920	41,307.5	5	00HDPG0014	110
Bristol	7	E01014647	19,149.0	1	00HBPL0035	123
Bristol	8	E01014515	21,753.0	2	00HBNR0010	119
Bristol	9	E01014489	25,357.0	3	00HBNM0037	104
Bristol	10	E01014621	44,992.0	5	00HBPG0010	101
Reading	1	04CDE01016358	29,074.5	2	00MCMS0003	70
Reading	2	04CDE01016430	55,399.5	5	00MCNF0017	107
Reading	3	04CDE01016365	39,771.5	4	00MCMT0032	118
Reading	4	04CDE01016613	35,866.0	3	00MFND0006	122
Reading	5	04CDE01016660	43,725.0	4	00MFNP0020	103
Reading	6	04CDE01016406	29,202.5	2	00MCNB0002	96
Reading	7	04CDE01016654	44,497.0	5	00MFNM0005	105
Reading	8	04CDE01016442	25,775.5	1	00MCNH0020	104
Reading	9	04CDE01016394	19,621.0	1	00MCNA0011	90
Reading	10	04CDE01016431	37,025.0	3	00MCNG0027	104
Leeds	1	08DAE01011686	19,053.5	1	08DAGG0063	120
Leeds	2	08DAE01011509	31,328.0	4	08DAFT0049	129
Leeds	3	08DAE01011353	37,158.0	5	08DAFG0062	140
Leeds	4	08DAE01011722	21,224.0	2	08DAGJ0005	119
Leeds	5	08DAE01011615	23,390.5	3	08DAGB0009	131
Leeds	6	08DAE01011490	26,725.0	4	08DAFS0014	167
Leeds	7	08DAE01011519	25,488.0	3	08DAFU0001	252
Leeds	8	08DAE01011604	34,094.0	5	08DAGA0041	119
Leeds	9	08DAE01011729	21,823.0	2	08DAGK0082	94
Leeds	10	08DAE01011371	16,057.0	1	08DAFH0017	138
Edinburgh	1	14S01002275	19,690.5	1	60QP003415 & 60QP000367	134
Edinburgh	2	14S01002167	25,694.0	2	60QP003555 & 60QP001083	131
Edinburgh	3	14S01002119	21,639.0	1	60QP001209 & 60QP001210	105
Edinburgh	4	14S01001575	25,728.0	2	60QM000074 & 60QM000083	112
Edinburgh	5	14S01001830	48,499.0	5	60QP001561 & 60QP001562	89
Edinburgh	6	14S01001850	28,159.0	3	60QP003782 & 60QP003781	98
Edinburgh	7	14S01001862	42,815.0	5	60QM002381 & 60QM002387	110
Edinburgh	8	14S01002123	42,648.5	4	60QP003058 & 60QP002124	108
Edinburgh	9	14S01002043	31,370.0	3	60QP001900 & 60QP001903	92
Edinburgh	10	14S01001924	40,388.0	4	60QP001404 & 60QP001401	107

3. Modelling plant-pollinator community robustness

Contents

3.1. Introduction

Community robustness with respect to secondary extinctions is a measure of the number of primary species removals (removals that may cause subsequent cascading extinctions) that a network can sustain before no species remain. The conventional approach to assessing this type of robustness requires multiple simulations per network[17-21]. Thus each simulation proceeds as follows: i) a primary species removal is made; ii) the network is checked to see if any remaining species are left without any resources and, if so, those species become secondarily extinct and are also removed from the network; and iii) additional primary removals are made (and any secondary extinctions recorded) until all species have been removed from the network. After multiple simulations with different removal sequences for the primary species, the robustness of a network is calculated as the average number of primary removals required for all species to be removed from the network. Due to constraints on time and computation, 1000 simulations are typically used for determining the robustness of a network[17,19]. (This is out of $S!$ possible primary removal sequences, which, for example, for $S = 30$ species is $30! = 2.6\text{x}10^{32}$.) As 90 networks have been sampled for each city in this study, the conventional secondary extinctions approach is not practical.

The limitations of the approach are even more pronounced when including the effect of species dispersal. As dispersal has the potential to introduce replacement species into the network, and thus prevent species from becoming primarily or secondarily extinct, there is the possibility for a network to never reduce in size, thereby preventing robustness from being calculated.

To avoid these problems, we used a secondary extinctions approach based on Bayesian networks to investigate community robustness, this including the effect of pollinator dispersal and switching behaviour (resource switching by pollinator species, also termed "rewiring"[20]). A Bayesian network approach is both computationally faster and more efficient than the simulation approach described above. It is also more appropriate for modelling dispersal, as primary removals and replacement species do not need to be simulated individually. Our approach is based on the method presented in Eklöf *et al.* (2013)[20], which considered the robustness to secondary extinctions of binary and weighted food webs generated using the Allometric Trophic Network model[20]. Among other results, they show that the measure of robustness using Bayesian networks is equivalent to the robustness from simulations of all *S*! possible primary removal sequences. As with any bottom-up secondary extinction analysis, top-down effects are not considered, but Eklöf *et al.* showed that the overestimation of community robustness (because top-down extinctions are not possible) is not very large [20].

Motivated by empirical plant-pollinator systems, we have extended the Bayesian network approach in Eklöf *et al.* (2013)[20] to include three new features:

1) Vulnerabilities of pollinator species to primary extinction are calculated separately from plant species, but we still allow for variation of extinction risk among pollinator species and among plant species;
2) Resource switching behaviour by pollinator species;
3) Pollinator species dispersal from surrounding land uses.

Below we give an overview of the Bayesian network approach and our particular implementation, followed by descriptions of the three extensions, and end with the procedure for investigating the effect of changes in citywide land use composition and quality on pollinator community robustness (Figs. 5a and 5b, main text).

3.2 Model overview

In general terms, the model incorporates differing inherent extinction risk among species, resource switching behaviour by consumers, species dispersal into networks from surrounding land uses, and community structure. In this study, the model is used to investigate the effect of land use change on pollinator dispersal and pollinator community robustness.

In the Bayesian network approach, we first specify a *prior* probability of extinction for each species in a network. This represents the probability of losing a species from the network when all of its resources are present and, therefore, before network structure is taken into account. In this study we set the prior extinction for a pollinator species to the product of its *vulnerability* of extinction, a probability set inversely proportional to its abundance, and a *dispersal factor*, which decreases the vulnerability in proportion to the number of individual pollinators of that species found in surrounding land uses.

When considering secondary extinctions, network structure, which indicates dependencies between species, serves to increase the probability of extinction. This is because priors only hold when all species in the network are extant and remain so. In assessing the effect of network structure, we are interested in understanding how the loss of different species in different combinations increases the extinction probability of other species in the network. The probability of extinction after taking into account network structure is known as the *posterior* probability (of extinction). Resource switching by pollinators (or, indeed, any consumer species) is implemented as part of the calculation from prior to posterior.

For bipartite networks with plant species at the lower trophic level, posteriors for plant species are always equal to their priors, and, as we are not modelling plant dispersal, prior and posterior for a given plant species are simply equal to their corresponding value for vulnerability.

We refer to plant-pollinator networks sampled at the same location as *local networks* (as distinct from, say, a network constructed from all recorded visits across a single city). For each pollinator species in each local network we have:

Prior (vulnerability x dispersal) → network structure (incl. switching) → posterior

which in symbols can be written for pollinator species j in local network l as

$\pi_{j,l} = V_j \times D_j$ → network structure (incl. switching) → $p_{j,l}$

In this study, unlike in Eklöf *et al.* (2013)[20], we use the sum of posteriors of pollinator species as our measure of community robustness. This measure is well suited to our purpose because the greater the expected loss of pollinator species, the lower the robustness of the network. The *expected pollinator loss* for a local network is

$$L_l = \sum_j p_{j,l} \ ;$$

and the expected loss of pollinator species at the city level is the sum over all local networks in a city:

$$L = \sum_l L_l = \sum_l \sum_j p_{j,l} \ .$$

We investigate the effect on the expected loss of pollinator species at the city level under different land use change scenarios. In the model, changing the relative land use composition of a city affects the amount of dispersal possible and hence pollinator species posterior values. For example, increasing the amount of gardens in a city may increase the numbers of pollinators in neighbouring regions that could disperse into the region represented by a local network, thereby increasing community robustness as measured using posterior values. In this way, a decrease in expected pollinator loss is synonymous with an increase in community robustness. For reference, a list of symbols is included in Section 3.9.

3.3 Species vulnerability to local extinction

The vulnerability of a plant or pollinator species represents the probability of a species becoming extinct given the presence of all its resources (before taking into account dispersal, which is discussed below). When each local network is analysed, the vulnerability of a plant or pollinator species to local extinction is set inversely proportional to its citywide density. In this way, we assume that the more abundant species at the city level are less likely to become locally extinct than those that are less abundant.

We calculate the set of vulnerabilities for plant species separately from pollinator species. Below we describe the calculation for pollinator species (an identical procedure is followed for plant species, i.e., with i indices instead of j indices).

The density of pollinator species j in local network l is $n_{j,l}$. An approximate value for $n_{j,l}$ is found by summing the number of recorded visits of j in l. The citywide density of pollinator species j is the total number of recorded visits summed across all local networks:

$$N_j = \sum_l n_{j,l} \, .$$

The set of citywide densities is then $\log_{10}$-transformed and linearly mapped to the range [-6,6]:

$$N'_j = 6\left[\frac{2\left(\log_{10} N_j - \min\left(\log_{10} \vec{N}_j\right)\right)}{\max\left(\log_{10} \vec{N}_j\right) - \min\left(\log_{10} \vec{N}_j\right)} - 1\right];$$

where an overhead arrow indicates a vector of values (in this expression, $\vec{N}_j$ is a vector of all citywide pollinator species densities). The range [-6,6] ensures an efficient mapping when using the logistic function in the next step.

These mapped values are then scaled to the range [0,0.6] using a logistic function:

$$V'_j = \frac{0.6}{1+e^{N'_j}} \, .$$

The final set of pollinator species vulnerabilities is calculated as

$$V_j = 0.2 + \frac{n_{poll}\left(0.5-0.2\right)}{\sum_j V'_j} V'_j \, ;$$

where n_{poll} is the total number of pollinator species in the city; the leading 0.2-value is an offset that gives values for the vulnerability in the range [0.2,0.8]; and the fraction in front of V'_j sets the average of pollinator species vulnerabilities to 0.5.

An identical procedure results in n_{plant} vulnerabilities for plant species (denoted by V_i).

In summary, the larger the citywide abundance of a species the lower its value for vulnerability, i.e. it has a lower probability of becoming locally extinct as a primary extinction.

3.4 Example of calculating expected pollinator loss for a small network

Consider a visitation network comprising a single pollinator species and a single plant species. The pollinator species is relatively rare and has $V_{j=1} = 0.7$ while the plant species is slightly more abundant than average and has $V_{i=1} = 0.4$.

The posterior probability of the plant species becoming locally extinct remains 0.4. However, the posterior probability of the pollinator species will be higher than 0.7 because there is the additional possibility that the plant species it visits becomes locally extinct and causes it to become secondarily extinct (dispersal is not being considered in this example). The posterior probability $p_{j=1,l=1} = 0.4 \times 1 + (1-0.4) \times 0.7 = 0.82$; where the first term represents the plant species becoming locally extinct and causing the pollinator species to become secondarily extinct, and the second term represents the pollinator becoming extinct while the plant species remains extant.

The expected pollinator loss for a local network is the sum of posterior probabilities of pollinator species:

$$L_l = \sum_j p_{j,l} \;;$$

which for this network is $L_{l=1} = 0.82$.

Compare this to a second local network in which the pollinator species is recorded visiting a more abundant plant species which has $V_{i=2} = 0.2$. The posterior probability for the pollinator species is $p_{j=1,l=2} = 0.2 \times 1 + (1-0.2) \times 0.7 = 0.76$; and so $L_{l=2} = 0.76$, which is lower than for the first network.

The expected pollinator species loss for a city is

$$L = \sum_l \sum_j p_{j,l} \;;$$

and if our city in this example only comprises the above two local networks then $L = 0.82 + 0.76 = 1.58$ (where the maximum possible value is two—from the expected loss associated with the single pollinator species in the first local network being one and the expected loss of the single pollinator species in the second local network also being one).

3.5 Resource switching by pollinator species

The number and identities of plant species that any given pollinator species is recorded visiting can vary between local networks in the same city. Often, no visit is recorded in a local network between a pollinator and plant species, even though the interaction is known to be possible based on recorded visits in other local networks. It is conceivable that individuals of the pollinator species could initiate the possible but unrecorded interaction (a switch) following the local extinction of one or more of the plant species it was recorded visiting in the local network[18,19].

We incorporate this switching behaviour into the Bayesian network approach using a new scheme which we call *minimum effective weight transfer*. Switching is modelled by modifying entries in the state tables used to determine the probability of local extinction of a given pollinator species under different resource states, i.e., when different combinations of plant species are present in the local network. As such, it is part of the calculation from prior to posterior probabilities of local extinction owing to network structure. Naturally, switching reduces the expected pollinator species loss compared to when switching is not considered.

The scheme is most easily explained using a simple example.

Consider a local network comprising the two species introduced above that have $V_{j=1} = 0.7$ and $V_{i=1} = 0.4$, but now suppose that 10 visits were recorded between the species. Also suppose that 5 visits were recorded between the pollinator species and the second plant species that has $V_{i=2} = 0.2$, giving a three-species network with two weighted interactions.

When a pollinator species visits more than one plant species, the weight of interaction (the number of recorded visits) becomes relevant when calculating the posterior probability of local extinction of the pollinator species.

In this study, we consider a *linear response* to resource loss, in which the probability of pollinator j becoming locally extinct, $x_{j,l}$, depends linearly on the fraction of resource weight that remains incident to it in the network:

$$x_{j,l} = V_j + \left(1 - V_j\right) f \; ;$$

where f is the fraction of resource weight lost by the pollinator species in given resource state[20].

For example, with the linear response we can construct the state table for the pollinator species in our simple three-species network. A "1" in the left-hand side of the table indicates that the corresponding plant species is locally extinct, while a "0" indicates that it is extant. With two plant species there are $2^2 = 4$ entries in the state table, one row for each distinct state of resources.

State table for pollinator species

$i=1$	$i=2$	$x_{j=1,l=3}$
1	1	1.0
1	0	0.9
0	1	0.8
0	0	0.7

From this table we can calculate the posterior probability of local extinction for the pollinator species:

$$p_{j=1,l=3} = 0.4 \text{ x } 0.2 \text{ x } 1 + 0.4 \text{ x } (1\text{-}0.2) \text{ x } 0.9 + (1\text{-}0.4) \text{ x } 0.2 \text{ x } 0.8 + (1\text{-}0.4) \text{ x } (1\text{-}0.2) \text{ x } 0.7$$

$$= 0.08 + 0.288 + 0.096 + 0.336$$

$$= 0.8$$

Now consider the presence of a third plant species in the network that has $V_{i=3} = 0.5$ and is a switch (a potential interaction) for the pollinator species.

We can construct a new state table that takes into account the possibility of switching behaviour. In this case, if one or both of the first two plant species is locally extinct then the minimum weight (in this case 5 visits) can be transferred to the third pollinator*. In the new state table, below, we highlight states where such a transfer takes place in **underlined-bold**. As the pollinator now visits three plant species, there are $2^3 = 8$ distinct resource states:

State table for pollinator species taking into account switching behaviour

i=1	*i=2*	*i=3*	$x_{j=1,l=3}$
1	1	1	1.0
1	0	1	0.9
0	1	1	0.8
0	0	1	0.7
1	1	0	**0.9**
1	0	0	**0.8**
0	1	0	**0.7**
0	0	0	0.7

The calculation of the posterior probability incorporating switching behaviour is

$$p_{j=1,l=3} = 0.4 \text{ x } 0.2 \text{ x } 0.5 \text{ x } 1 + 0.4 \text{ x } (1\text{-}0.2) \text{ x } 0.5 \text{ x } 0.9$$

$$+ (1\text{-}0.4) \text{ x } 0.2 \text{ x } 0.5 \text{ x } 0.8 + (1\text{-}0.4) \text{ x } (1\text{-}0.2) \text{ x } 0.5 \text{ x } 0.7$$

$$+ 0.4 \text{ x } 0.2 \text{ x } (1\text{-}0.5) \text{ x } 0.9 + 0.4 \text{ x } (1\text{-}0.2) \text{ x } (1\text{-}0.5) \text{ x } 0.8$$

$$+ (1\text{-}0.4) \text{ x } 0.2 \text{ x } (1\text{-}0.5) \text{ x } 0.7 + (1\text{-}0.4) \text{ x } (1\text{-}0.2) \text{ x } (1\text{-}0.5) \text{ x } 0.7$$

$$= 0.04 + 0.144 + 0.048 + 0.168 + 0.036 + 0.128 + 0.042 + 0.168$$

$$= 0.774$$

which results in a lower value than the case in which switches were not considered.

*This is a conservative estimate of the effect of a switch because the smallest observed weight for a pollinator species is being transferred. However, this choice prevents the total weight (number of visits) incident on the pollinator exceeding its observed value when modelling a switch.

So the expected pollinator species loss is $L_{l=3} = 0.8$ when the possibility for switching is not considered, but reduces to $L_{l=3} = 0.774$ when switching behaviour is modelled in this way.

When applying the minimum effective weight transfer scheme to local networks in a city, a reference network is first formed from the complete set of recorded interactions. This reference network lists all of the visits that were recorded between plant and pollinator species, which is used to identify which interactions are possible switches when calculating the expected pollinator species loss in a local network.

For networks larger than a few species, it is not practical to calculate posteriors in the way described above—i.e. by hand. Rather, algorithms such as the *junction tree algorithm* are used to efficiently compute posteriors from state tables[20]. We use the *R* package *gRain v1.1-1* to compute posteriors[21].

There is no change in the qualitative results presented in Fig. 5, main text, if switches are considered or not.

3.6 Pollinator species dispersal from surrounding land uses

In the model the dispersal of pollinator species from surrounding land uses into that of the network being analysed can reduce prior probabilities of extinction, and therefore increase community robustness compared to when dispersal is not considered.

When calculating dispersal factors for each pollinator species in each local network, we first estimate the *capacity* of land use k for pollinator species j as

$$C_{j,k} = \frac{F_k}{n_{j,k}};$$

where F_k is the floral density of the land use (number of floral units across plant species per m^2) and $n_{j,k}$ is the density of pollinator species j in land use k (which can be estimated from network visitation data). The capacity therefore expresses the number of floral units per individual pollinator of a particular species in a given land use.

From the capacity, we can define a *movement factor* that describes the tendency for a pollinator species to move from one land use to another. For each pollinator species, a set of raw movement factors is calculated based on the difference in capacities between each pair of land uses—one capacity for the surrounding land use k and another for the land use k' of the local network:

$$M'_{j,k,k'} = \frac{1}{C_{j,k}} - \frac{1}{C_{j,k'}}.$$

Raw movement factors are scaled to the range [0,1] in a similar procedure as for calculating species vulnerabilities.

First the raw values are linearly mapped to the range [-6,6]:

$$M''_{j,k,k'} = 6\left[\frac{2\left(M'_{j,k,k'} - \min\left(\vec{M}'_{j,k,k'}\right)\right)}{\max\left(\vec{M}'_{j,k,k'}\right) - \min\left(\vec{M}'_{j,k,k'}\right)} - 1\right];$$

and then scaled to the range [0,1] using a logistic function:

$$M_{j,k,k'} = \frac{1}{1 + e^{-M''_{j,k,k'}}}$$

where $M_{j,k,k'} = 0.5$ if $k = k'$, and $M_{j,k,k'} = 0$ if pollinator species j is not found in land use k.

With this formulation, pollinator species are more likely to move from land uses with low capacity to those with high capacity.

Next, we estimate the number of individual pollinators that we can expect to find in land uses surrounding the site of each local network. Individual pollinators are measured to obtain representative body sizes for each pollinator species, which are used to classify each species into six categories according to size. A dispersal range is calculated for each category using the established relationship between the log of intertegular span and the log of foraging distance given by Greenleaf *et al.* (2007)[22].

We consider two forms of dispersal range: maximum homing distance and maximum typical foraging distance (Table D). Results were qualitatively similar for the two dispersal forms.

Table D. Pollinator size categories and distances calculated following Greenleaf *et al.* (2007)[22]

Size category	Size range (mm)	Homing distance (m)	Foraging distance (m)
1	0 to 0.99	93	233
2	1 to 1.99	463	703
3	2 to 2.99	978	1174
4	3 to 3.99	1597	1646
5	4 to 4.99	2306	2199
6	5 to 5.99	3093	2592

Using these dispersal distances and GIS software, we obtained a breakdown by area of surrounding land uses for each pollinator species in each local network. The land use data set created (described in Supplementary Methods Part 1) was used as the basis for calculating the proportion of land uses within the homing distance and foraging distance of each site. A buffer for each homing distance and foraging distance was created in ArcGIS 10. Then a 'polygon in polygon' analysis (in the Geospatial Modelling Environment[23]) was used to determine the proportion of each land use found within each distance of each site based on the area within the buffer. We denote by $A^*_{j,k,l}$ the area in m^2 of surrounding land use k found within the circular dispersal range of pollinator j in local network l.

Before considering area change scenarios, we first calibrate the dispersal model using empirical area values ($A^*_{j,k,l}$).

Reference dispersal factors are calculated for each pollinator species in each local network as

$$D^*_{j,l} = 2\sum_k n_{j,k} A^*_{j,k,l} M_{j,k,k'};$$

where the sum is over surrounding land uses and k' is the land use of local network l. The expression is the product of the number of individuals of pollinator species j that are expected to be found in the k^{th} surrounding land use, $n_{j,k} A^*_{j,k,l}$, and the movement factor $M_{j,k,k'}$, which is larger for dispersal from surrounding land uses that are at lower capacity than the land use of the local network.

Given an area change scenario with new $A_{j,k,l}$, the dispersal factor $D_{j,l}$ for pollinator species j in local network l is calculated using the following procedure.

Raw dispersal factors are calculated with the new $A_{j,k,l}$ using a similar expression to that of reference dispersal factors:

$$D'_{j,l} = \sum_k n_{j,k} A_{j,k,l} M_{j,k,k'};$$

which are then linearly mapped to the range [-6,6] according to reference dispersal factors:

$$D''_{j,l} = 6\left[\frac{2D'_{j,l}}{D^*_{j,l}} - 1\right];$$

and finally scaled to the range [0.5,1] using a logistic function:

$$D_{j,l} = 0.5 + \frac{0.5}{1 + e^{D''_{j,l}}}.$$

With this procedure, empirical area values ($A^*_{j,k,l}$) are set to result in $D_{j,l} = 0.75$. If there is no dispersal (for example, $A_{j,k,l} = 0$, for all k) we have $D_{j,l} = 1$, and the prior is equal to the vulnerability of the pollinator species. If a raw dispersal factor is twice that when calculated for $A^*_{j,k,l}$, for example, if the area contributing to dispersal is doubled ($A_{j,k,l} = 2 \text{ x } A^*_{j,k,l}$ for all k, which leads to $D_{j,l} = D^*_{j,l}$), then $D_{j,l} = 0.5$, which represents the maximum possible effect of dispersal with this model.

3.7 Strategy analysis

For each pollinator species j in local network l, the model describes the process of obtaining prior probabilities of extinction $\pi_{j,l}$ and then calculating posterior probabilities of extinction $p_{j,l}$:

$\pi_{j,l} = V_j \times D_{j,l}$ → network structure (incl. switching) → $p_{j,l}$

From posterior probabilities we can calculate the expected loss of pollinator species in a local network as

$$L_l = \sum_j p_{j,l} \,;$$

and the expected loss of pollinator species at the city level as

$$L = \sum_l L_l = \sum_l \sum_j p_{j,l} \,.$$

Each set of surrounding land use areas ($A_{j,k,l}$) results in a single value for the expected loss of pollinator species at the city level. A single value for the expected loss of pollinator species is not especially informative. However, multiple values can be compared to assess the relative effect of different land use-change scenarios on pollinator community robustness.

i. Strategy 1: Increasing land use area (quantity)

Consider a single land use. We can assess the effect of changing the relative amount of that land use in the city on expected pollinator loss through its effect on dispersal. We model seven area change scenarios per land use: no change in the area of the single land use being considered (100% of observed area); an increase to 125% of observed area, 150% and 175%; and a decrease to 25% of observed area, 50% and 75%.

Each scenario results in a new value for the expected pollinator species loss at the city level. These seven values (25%, 50%, 75%, 100%, 125%, 150% and 175%) per land use form the set of lines in Fig. B. The change in dispersal area under different scenarios (x-axes in Fig. B) is simply the difference between the area contributing to dispersal under a scenario and the total dispersal area A^* when empirical values are used in the model, where

$$A^* = \sum_l \sum_k \sum_j A^*_{j,k,l} \,;$$

which is the zero-point on the x-axes in Fig. B.

To enable comparison among cities, the expected pollinator species loss L is scaled to the range [-1,1] between the maximum and minimum loss possible in the model. The maximum expected loss $L_{\max}$ results when no dispersal is considered, i.e., $D_{j,l} = 1$ for all j and l; while the minimum expected loss $L_{\min}$ results when all dispersal factors are set to their smallest permissible value, i.e.,

$D_{j,l} = 0.5$ for all j and l. The change in expected pollinator species loss from the value L^* when empirical area values, $A^*_{j,k,l}$, are used (y-axes in Fig. B) is then

$$\Delta_L = \frac{2(L - L_{\min})}{L_{\max} - L_{\min}} - 1\ ;$$

where because, as stated above, empirical area values are set to result in $D_{j,l} = 0.75$ for all j and l, we have $L(A^*_{j,k,l}) = L^* = (L_{\max} - L_{\min})/2$, which gives $\Delta_{L^*} = 0$, as required.

The gradient of each land-use curve (25%, 50%, 75%, 100%, 125%, 150% and 175% area change scenarios) is a measure of land use importance, where larger gradients indicate more important land uses. This is because for large gradients, only a relatively small change in area is necessary to affect a large change in expected pollinator species loss and, hence, change in pollinator community robustness.

In addition to changes in citywide land use composition, we can use the above approach to assess the effect of changes in land use quality on pollinator community robustness. Recall that raw dispersal factors in the area-change scenario are written as

$$D'_{j,l} = \sum_k n_{j,k} A_{j,k,l} M_{j,k,k'}\ .$$

ii. Strategy 2: Improving land use quality

We model improving land use quality by simulating the addition of extra plants to a particular land use, which requires an extra term in the expression for raw dispersal factor, which becomes

$$D'_{j,l} = \sum_k \left(n^+_{i,k} n_{i,j,k} + n_{j,k}\right) A_{j,k,l} M_{j,k,k'}\ ;$$

where $n^+_{i,k}$ is the number of units of plant species i added to land use k per unit area and $n_{i,j,k}$ is the expected number of visits of pollinator j to plant species i in land use k per unit area (approximate values for $n_{i,j,k}$ can be calculated from network visitation data). As such, $n^+_{i,k}\, n_{i,j,k}\, A_{j,k,l}$ represents the number of additional individuals for pollinator species j due to adding the extra plants of species i in land use k.

A similar scaling of these new dispersal factors to reference dispersal factors can be followed as described above to quantify the effect of adding different sets of plant species on expected pollinator species loss at the city level. We present results for adding a set of three plant species (*Bellis perennis*, *Trifolium repens*, and *Taraxacum* agg.) to three land uses separately (other greenspace, parks and road verges, Fig. 5b, main text). These plants were chosen because they were commonly found in these three land uses, and we recorded pollinators visiting these plants at all sampling sites for these land uses across all four cities. For the rationale behind selection of these three land uses, see main text. In simulations, we add plant units of the focal species until there is no change in expected pollinator species loss (i.e., results are for large $n^+_{i,k}$), which means we are comparing best-case scenarios among the three land uses.

3.8 Comparing the effects of increasing area among land uses

The in-silico experiments described above (results presented in Fig. B) were designed to quantify the effect of changes in land use area on plant-pollinator community robustness. As absolute area can vary among land uses by a large amount within a city, we simulated percentage changes in area (e.g., increases of 25%, 50% and 75% of the observed area in each city, Fig. B). We focus on increases in area rather than decreases because we are interested in opportunities for pollinator conservation; note though that the effects of land use gain and loss are symmetrical, i.e. the positive gains of increasing the area of a good pollinator habitat are seen as equivalent negative losses if this land use is decreased. The changes in robustness (changes in expected pollinator loss) resulting from these simulated changes in land-use area are shown in Table E. Because the changes in robustness are based on *relative* increases in area, each robustness value is associated with a different amount of area that has been added to the city. To facilitate comparison among land uses, each increase in robustness was divided by the *absolute* increase in area to provide an increase in robustness per m^2. For presentational clarity in Fig. 5a. main text, we multiplied increases in robustness per m^2 by a fixed area of 100,000 m^2, which is equivalent to 10 ha. Note that the models simulate an increase in land use area within the pollinator dispersal distances around each site (i.e., a 25% increase in allotments corresponds to a 25% increase in the area of allotments in the dispersal distances around each site, rather than an area equal to 25% of the total area of allotments across the entire city). However given that there are 90 sites per city these areas represent a large proportion of each city.

Consider the following worked example for allotments in Bristol. Increasing the amount of allotments by 25% would correspond to adding 52,354 m^2 of this particular land use. The corresponding increase in robustness from our simulation was 0.106 (Table E). The per unit area-squared change in robustness for this pair of values is 0.106 / 52,354 m^2 = 2.03×10^{-6} robustness / m^2. Using this value (which is associated with a 25% increase in area), the expected increase in robustness following the addition of 10 ha of allotments is $2.03 \times 10^{-6} \times 100{,}000\ m^2 = 0.203$, which is the value plotted in Fig. 5a. For the 50% area change, the steps are 0.167 / (2 x 52,354 m^2) = 1.59×10^{-6}; then $1.59 \times 10^{-6} \times 100{,}000\ m^2 = 0.159$.

3.9 List of symbols

i	index for plant species
j	index for pollinator species
k	index for land uses
l	index for local networks
$n_{i,l}$	density of a plant species in a local network
$n_{j,l}$	density of a pollinator species in a local network
$n_{i,k}$	density of a plant species in a particular land use
$n_{j,k}$	density of a pollinator species in a particular land use

$n_{i,j,k}$ density of a pollinator species visiting a plant species in a particular land use

N_i citywide density of a plant species

N_j citywide density of a pollinator species

n_{plant} number of plant species in a city

n_{poll} number of pollinator species in a city

V_i vulnerability to local extinction of a plant species

V_j vulnerability to local extinction of a pollinator species

$\pi_{j,l}$ prior probability of local extinction of a pollinator species

$p_{j,l}$ posterior probability of local extinction of a pollinator species

L_l expected pollinator loss for a local network

L expected pollinator loss at the city-level

$x_{j,l}$ local extinction probability of a pollinator species for a given resource state

f fraction of resource weight lost by a pollinator species

$C_{j,k}$ capacity of a land use for a pollinator species

F_k floral density of a land use

$M_{j,k,k'}$ movement factor of a pollinator species dispersing from surrounding land use k to land use k' of the local network

$A_{j,k,l}$ area of land use in the dispersal range of a pollinator species in a local network

$D_{j,l}$ dispersal factor of a pollinator species in a local network

Figure B. Robustness change of plant-pollinator communities in the four cities under different land use area changes

Robustness of plant-pollinator communities in four UK cities, measured as the effect of additional land use area on expected pollinator loss (scaled between the minimum and maximum loss possible, [-1,1], according to a secondary extinctions model). Note that a reduction in expected pollinator loss due to adding land use area is the same as an increase in robustness. For each land use, seven area change scenarios are shown per city: 0%, ±25%, ±50% and ±75% relative to the observed area surrounding 90 sampled plant-pollinator networks; the gradient of each line is a measure of land use importance with larger gradients indicating more important land uses, as small changes in area lead to relatively large changes in expected pollinator loss. Across all cities, increasing the area of gardens (GDN) results in the largest reduction in pollinator loss. But adding a much smaller area of allotments (ALT) leads to comparatively larger decreases in expected pollinator loss. Cemeteries (CEM) in Edinburgh and parks (PK) in Reading are also important land uses; but changes in area for pavements (PVT) and man-made structures (MMS) have little effect on pollinator communities. Increasing the areas of nature reserves (NR) and other greenspace (OGS) leads to intermediate decreases in expected pollinator loss.

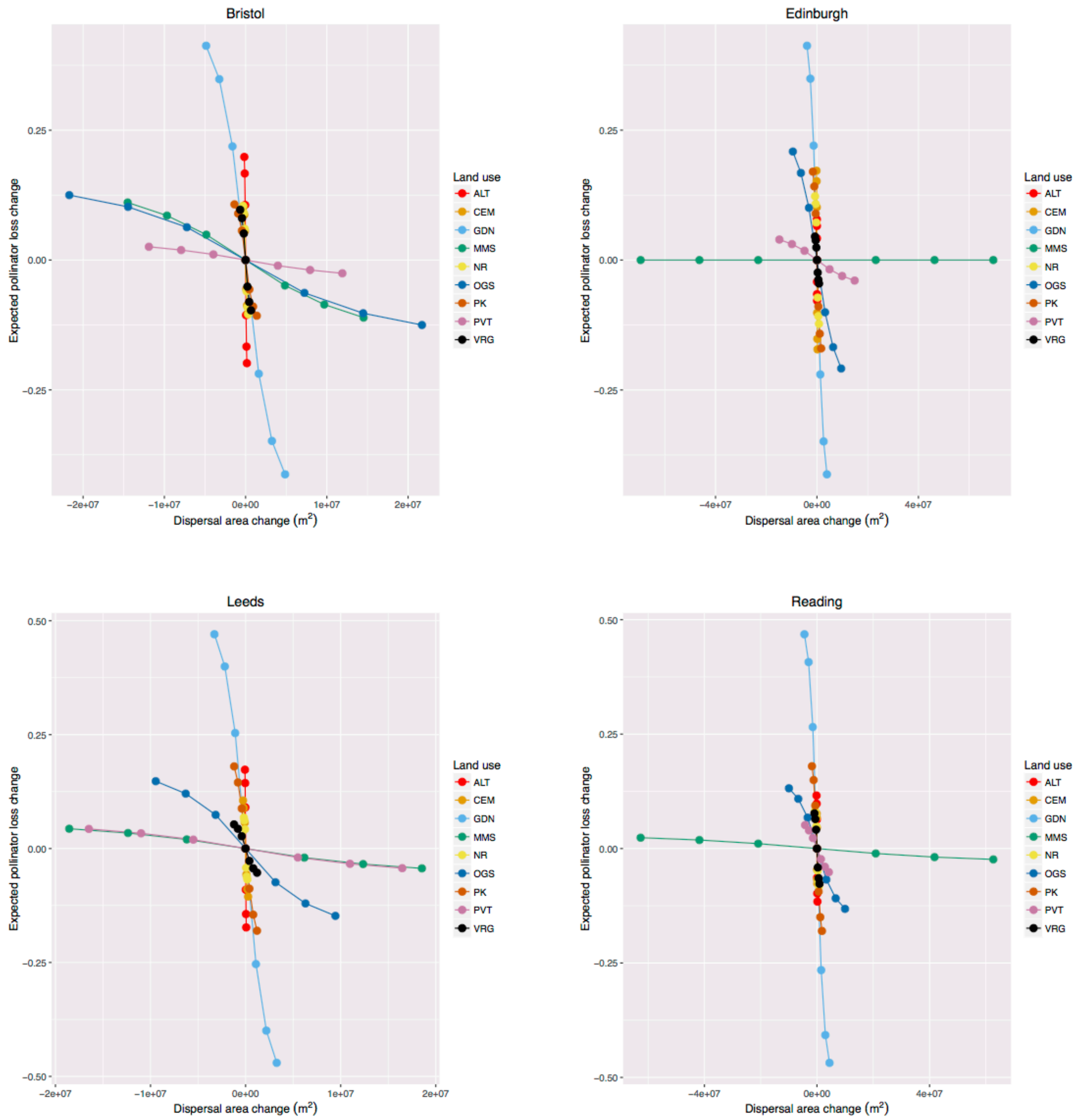


Table E. Increases in city-scale robustness (min: 0, max: 1) of plant-pollinator networks when areas of each urban land use are increased by 25%, 50% and 75% of current values

a. Bristol

	Area change								
	±25%			±50%			±75%		
	Robustness increase	Area added (m^2)	Robustness increase per m^2	Robustness increase	Area added (m^2)	Robustness increase per m^2	Robustness increase	Area added (m^2)	Robustness increase per m^2
Allotment	0.106	52,354	2.03×10^{-6}	0.167	104,707	1.59×10^{-6}	0.199	157,061	1.26×10^{-6}
Cemetery	0.056	84,898	6.58×10^{-7}	0.087	169,796	5.13×10^{-7}	0.103	254,694	4.04×10^{-7}
Garden	0.219	1,619,537	1.35×10^{-7}	0.348	3,239,073	1.08×10^{-7}	0.413	4,858,610	8.49×10^{-8}
Manmade surface	0.049	4,840,256	1.01×10^{-8}	0.086	9,680,509	8.85×10^{-9}	0.111	14,520,763	7.63×10^{-9}
Nature reserve	0.060	109,446	5.48×10^{-7}	0.091	218,892	4.15×10^{-7}	0.105	328,338	3.18×10^{-7}
Other greenspace	0.063	7,233,922	8.74×10^{-9}	0.102	14,467,843	7.08×10^{-9}	0.125	21,701,764	5.76×10^{-9}
Park	0.057	458,455	1.23×10^{-7}	0.090	916,910	9.77×10^{-8}	0.107	1,375,364	7.79×10^{-8}
Pavement	0.011	3,968,707	2.72×10^{-9}	0.019	7,937,410	2.42×10^{-9}	0.026	11,906,116	2.14×10^{-9}
Verge	0.051	220,596	2.32×10^{-7}	0.081	441,191	1.83×10^{-7}	0.097	661,786	1.46×10^{-7}

b. Reading

	Area change								
	±25%			±50%			±75%		
	Robustness increase	Area added (m^2)	Robustness increase per m^2	Robustness increase	Area added (m^2)	Robustness increase per m^2	Robustness increase	Area added (m^2)	Robustness increase per m^2
Allotment	0.063	53,514	1.18×10^{-6}	0.098	107,027	9.16×10^{-7}	0.116	160,541	7.22×10^{-7}
Cemetery	0.046	33,042	1.38×10^{-6}	0.068	66,084	1.03×10^{-6}	0.076	99,126	7.71×10^{-7}
Garden	0.265	1,486,082	1.79×10^{-7}	0.407	2,972,164	1.37×10^{-7}	0.468	4,458,246	1.05×10^{-7}
Manmade surface	0.011	20,880,706	5.15×10^{-10}	0.019	41,761,392	4.47×10^{-10}	0.024	62,642,089	3.79×10^{-10}
Nature reserve	0.049	223,354	2.18×10^{-7}	0.073	446,707	1.63×10^{-7}	0.083	670,060	1.24×10^{-7}
Other greenspace	0.068	3,323,526	2.04×10^{-8}	0.109	6,647,051	1.64×10^{-8}	0.132	9,970,577	1.32×10^{-8}
Park	0.094	591,715	1.59×10^{-7}	0.150	1,183,430	1.27×10^{-7}	0.180	1,775,146	1.01×10^{-7}
Pavement	0.023	1,402,252	1.65×10^{-8}	0.040	2,804,501	1.42×10^{-8}	0.051	4,206,752	1.22×10^{-8}
Verge	0.041	297,666	1.39×10^{-7}	0.065	595,331	1.09×10^{-7}	0.077	892,997	8.61×10^{-8}

c. Leeds

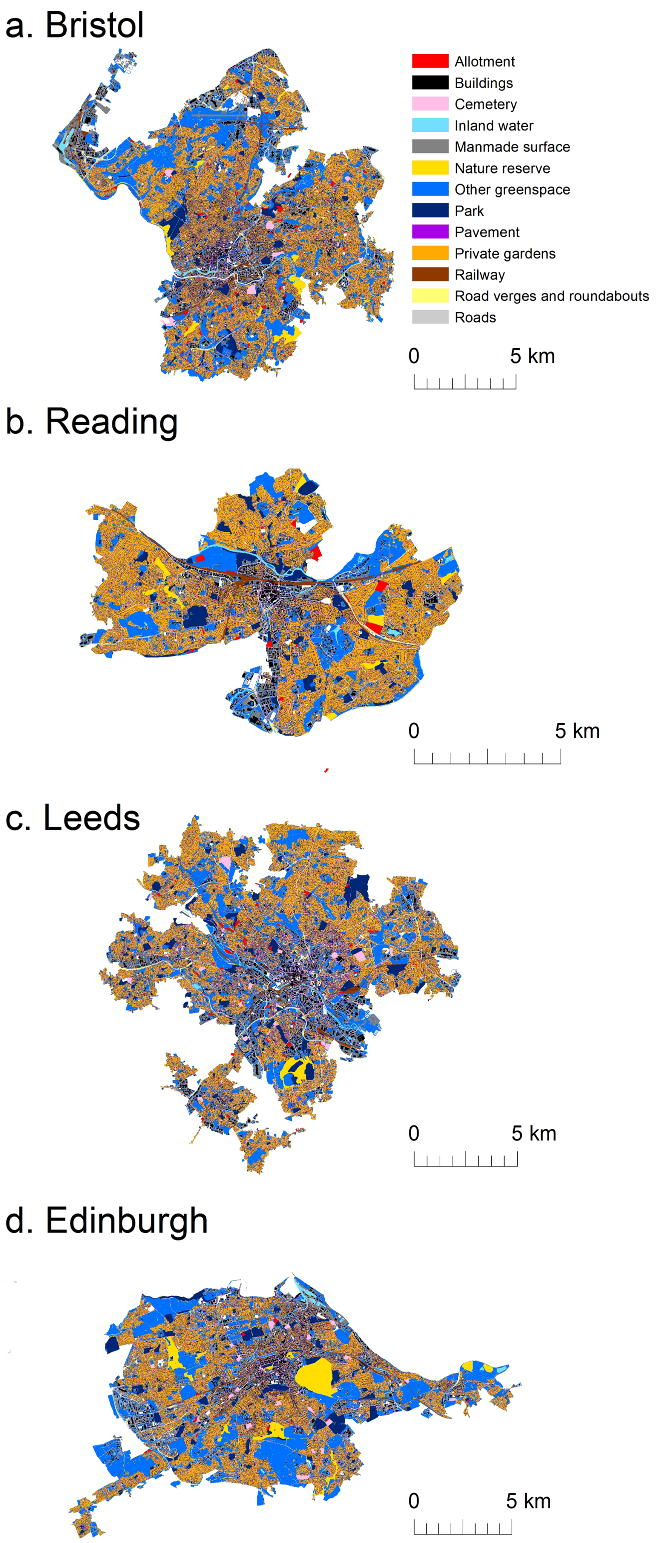
	Area change								
	±25%			±50%			±75%		
	Robustness increase	Area added (m^2)	Robustness increase per m^2	Robustness increase	Area added (m^2)	Robustness increase per m^2	Robustness increase	Area added (m^2)	Robustness increase per m^2
Allotment	0.090	23,228	3.89×10^{-6}	0.144	46,456	3.09×10^{-6}	0.173	69,683	2.48×10^{-6}
Cemetery	0.057	89,597	6.35×10^{-7}	0.089	179,194	4.98×10^{-7}	0.106	268,791	3.93×10^{-7}
Garden	0.253	1,092,563	2.32×10^{-7}	0.400	2,185,126	1.83×10^{-7}	0.470	3,277,689	1.43×10^{-7}
Manmade surface	0.020	6,181,365	3.23×10^{-9}	0.034	12,362,723	2.76×10^{-9}	0.044	18,544,085	2.35×10^{-9}
Nature reserve	0.042	61,496	6.88×10^{-7}	0.062	122,992	5.01×10^{-7}	0.068	184,488	3.67×10^{-7}
Other greenspace	0.074	3,148,793	2.35×10^{-8}	0.121	6,297,584	1.91×10^{-8}	0.148	9,446,376	1.56×10^{-8}
Park	0.088	400,666	2.20×10^{-7}	0.145	801,332	1.81×10^{-7}	0.180	1,201,998	1.50×10^{-7}
Pavement	0.020	5,493,430	3.56×10^{-9}	0.033	10,986,853	3.05×10^{-9}	0.043	16,480,279	2.62E-09
Verge	0.027	402,559	6.75×10^{-8}	0.043	805,118	5.39×10^{-8}	0.053	1,207,677	4.39×10^{-8}

d. Edinburgh

	Area change								
	±25%			±50%			±75%		
	Robustness increase	**Area added (m^2)**	**Robustness increase per m^2**	**Robustness increase**	**Area added (m^2)**	**Robustness increase per m^2**	**Robustness increase**	**Area added (m^2)**	**Robustness increase per m^2**
Allotment	0.042	14,097	2.97×10^{-6}	0.066	28,194	2.33×10^{-6}	0.078	42,291	1.85×10^{-6}
Cemetery	0.102	67,688	1.50×10^{-6}	0.152	135,376	1.12×10^{-6}	0.172	203,063	8.46×10^{-7}
Garden	0.220	1,307,335	1.68×10^{-7}	0.349	2,614,670	1.33×10^{-7}	0.412	3,922,005	1.05×10^{-7}
Manmade surface	0.000	23,172,021	2.68×10^{-13}	0.000	46,344,008	1.34×10^{-13}	0.000	69,516,016	8.94×10^{-14}
Nature reserve	0.072	257,865	2.80×10^{-7}	0.108	515,729	2.09×10^{-7}	0.123	773,593	1.59×10^{-7}
Other greenspace	0.101	3,173,778	3.17×10^{-8}	0.168	6,347,556	2.64×10^{-8}	0.209	9,521,334	2.19×10^{-8}
Park	0.089	544,241	1.64×10^{-7}	0.142	1,088,481	1.30×10^{-7}	0.170	1,632,722	1.04×10^{-7}
Pavement	0.018	4,946,172	3.61×10^{-9}	0.031	9,892,333	3.10×10^{-9}	0.039	14,838,499	2.66×10^{-9}
Verge	0.024	265,226	9.10×10^{-8}	0.038	530,450	7.16×10^{-8}	0.045	795,676	5.69×10^{-8}

Supplementary Figure 1. Land use maps for the four cities

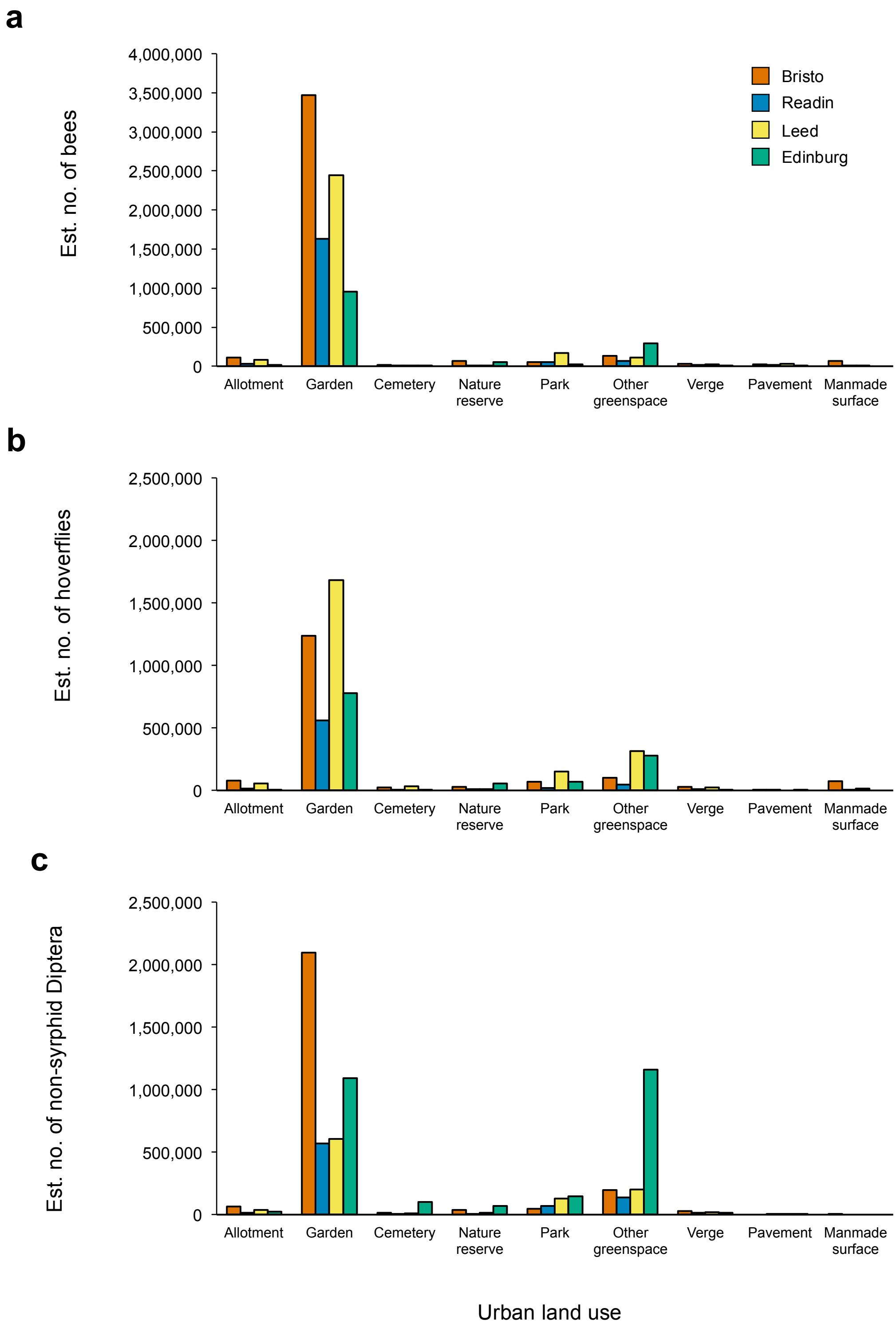
Land use maps showing the nine sampled land uses and unsampled land uses for **a.** Bristol, **b.** Reading, **c.** Leeds and **d.** Edinburgh. See Supplementary Methods for details of how the maps were created.



Supplementary Figure 2. Examples of the nine land uses sampled in the study

Supplementary Figure 5. Estimated numbers of bees, hoverflies and non-syrphid Diptera per land use at a city scale

Estimated numbers of **a.** bees, **b.** hoverflies and **c.** non-syrphid Diptera per land use at a city scale for the four cities.



Supplementary Table 1. Areas and proportions of land uses in the four cities

The area (hectares) of the nine sampled land uses and unsampled land uses in the four cities. Land use maps (Supplementary Fig. 1) were created using ArcGIS for each city (see Supplementary Methods). The areas are also shown as a proportion of each city's total area. Total city areas: Bristol: 14,505 ha, Reading: 6294 ha, Leeds: 13,974 ha, Edinburgh: 12,384 ha

Land use	Description	Bristol		Reading		Leeds		Edinburgh		Mean proportion across cities
		Area	Prop	Area	Prop	Area	Prop	Area	Prop	
Allotment	Includes council-managed and private allotments (equivalent to community gardens in the US)	115	0.008	63	0.010	83	0.006	30	0.002	0.007
Cemetery	Cemeteries, churchyards & burial grounds	95	0.007	31	0.005	120	0.009	109	0.009	0.007
Garden	Residential gardens	3992	0.275	2233	0.355	3917	0.280	2991	0.242	0.288
Nature reserve	Includes sites designated as Local Nature Reserves (LNR) and Sites of Special Scientific Interest (SSSI)	202	0.014	81	0.013	106	0.008	476	0.038	0.018
Manmade surface	Includes car parks and industrial areas	1500	0.103	419	0.067	1282	0.092	796	0.064	0.082
Other greenspace	Includes amenity grassland areas, golf courses and playing fields	3316	0.229	1185	0.188	2846	0.204	3463	0.280	0.225
Park	Sites designated as public parks according to council databases	447	0.031	365	0.058	717	0.051	688	0.056	0.049
Pavement	All public pavements (Equivalent to US sidewalks)	619	0.043	241	0.038	699	0.050	498	0.040	0.043
Verge	Road verges and roundabouts	243	0.017	142	0.022	297	0.021	155	0.012	0.018
Buildings	Not sampled	2239	0.154	843	0.134	2076	0.149	1661	0.134	0.143
Roads	Not sampled	1290	0.089	500	0.079	1491	0.107	1199	0.097	0.093
Railway (manmade)	Not sampled	124	0.009	54	0.009	100	0.007	75	0.006	0.008
Railway (natural)	Not sampled	52	0.004	39	0.006	60	0.004	51	0.004	0.005
Inland water	Not sampled	119	0.008	78	0.012	70	0.005	109	0.009	0.009
Tidal water and foreshore	Not sampled	41	0.003	0	0.000	0	0.000	8	0.001	0.001

Supplementary Table 2. Definitions of land use categories sampled in the four cities

Land use	Description	Equivalent terms in non-UK countries
Allotment	Council or privately owned land divided into individual plots managed by plotholders. Plots typically used to grow fruit, vegetables and flowers.	Community gardens (USA)
Cemetery	Private and publicly owned burial areas including cemeteries, churchyards and burial grounds	
Garden	Gardens adjacent to residential buildings and managed by residents. Comprises all areas categorised as “private gardens” according to Mastermap.	
Manmade surface	All areas categorised as “Other manmade surface” according to Mastermap data; typically car parks and industrial areas	
Nature reserve	Nature reserves designated as Local Nature Reserves (LNR) and Sites of Special Scientific Interest (SSSI)	
Other greenspace	Areas not allocated to any other land use and categorised as “Other natural surface” according to Mastermap data. Predominantly publicly accessible greenspace managed as amenity grassland, school playing fields and some woodland.	
Park	Public parks owned by local councils	
Pavement	Public walkways	Sidewalks (USA)
Road verges & roundabouts	Grass areas adjacent to roads and on roundabouts	Roundabouts = traffic circles (USA)

Supplementary Table 3. Results of GLMMs fitted with a negative binomial distribution testing for differences in pollinator abundance between the nine urban land uses for all pollinator taxa, Diptera, hoverflies, non-syrphid Diptera, Hymenoptera, bees. Significant pairwise Tukey *post hoc* comparisons are shown with all other pairwise comparisons non-significant ($p > 0.05$). Near-significant p-values are shown in brackets. Means and standard errors are calculated from the raw data. Findings are presented for models with and without outliers at two Edinburgh sites which recorded an unusually large number of visits by a single fly species (Scatopsidae: *Reichertella geniculata*). Alt: allotment, Cem: cemetery, churchyards & burial grounds, Gdn: garden, MMS: manmade surface, NR: nature reserve, OGS: other greenspace, P'ment: pavement. The significance of the other main effects (city and floral abundance) are included in the table. Tukey *post hoc* comparisons are shown for pairwise city comparisons. Br: Bristol, Rd: Reading, Ld: Leeds, Ed: Edinburgh. § indicates the *post hoc* test is no longer significant when models include outliers; † indicates the *post hoc* test becomes significant when the model includes outliers.

Taxon and sample size	**Land use**	**Mean ± 1SE**	**Effect of land use (df=8)**	**Comparison**	**Tukey *post hoc* tests**	**Effect of City (df=3)**	**Comparison**	**Tukey *post hoc* tests**	**Effect of floral abundance (df=1)**
All pollinator taxa	Allotment (outliers)	41.7 ± 6.6	Outliers not included:	Alt>Cem	(p=0.066)	Outliers not included:	Br-Ed	p=0.013	Outliers not included:
	Allotment (no outliers)	37.5 ± 4.8	χ^2 = 112.50, p< 0.0001	Alt>MMS	p< 0.001	χ^2 = 9.56, p=0.023	Br-Ld	p=0.740	χ^2 = 127.97, p<0.0001
n=4996	Cemetery	13.9 ± 2.1		Alt>OGS	p< 0.001		Br-Rd	p=0.174	
n=4515 (no outliers)	Garden	27.0 ± 2.3		Alt>Pk	p=0.016 §		Ed-Ld	p=0.178	
	Manmade surface	0.7 ± 0.4		Alt>P'ment	p< 0.001		Ed-Rd	p=0.728	
	Nature reserve	11.9 ± 2.1		Alt>Verge	p< 0.001		Ld-Rd	p=0.742	
	OGS (with outliers)	13.4 ± 8.9		Cem>MMS	p< 0.001				
	OGS (no outliers)	5.5 ± 1.2	Outliers included:	Cem>OGS	p= 0.014 §	Outliers included:	Br-Ed	p=0.282	Outliers included:
	Park	9.9 ± 1.3	χ^2 = 92.94, p< 0.0001	Cem>P'ment	p< 0.001	χ^2 = 3.75, p=0.290	Br-Ld	p=0.851	χ^2 = 116.30, p<0.0001
	Pavement	1.2 ± 0.3		Cem>Verge	p< 0.001		Br-Rd	p=0.421	
	Verge	5.4 ± 0.8		Gdn>MMS	p< 0.001		Ed-Ld	p=0.762	
				Gdn>OGS	p=0.001 §		Ed-Rd	p=0.993	
				Gdn>P'ment	p< 0.001		Ld-Rd	p=0.890	
				Gdn>Verge	p< 0.001				
				NR>MMS	p< 0.001				
				NR>OGS	p=0.006 §				
				NR>P'ment	p< 0.001				
				NR>Verge	p< 0.001				
				Park>MMS	p< 0.001				
				Park>OGS	(p= 0.082)				
				Park>P'ment	p< 0.001				
				Park>Verge	p< 0.001				
				OGS>MMS	(p=0.122) †				
				OGS>Pvt	p=0.003				

Diptera	Allotment (outliers)	23.0 ± 5.9	Outliers not included:	Alt>MMS	p<0.001	Outliers not included:	Br-Ed	p=0.729	Outliers not
n=2952	Allotment (no outliers)	18.8 ± 3.4	χ^2 = 87.03, p< 0.0001	Alt>OGS	p=0.010 §	χ^2 = 5.59, p=0.134	Br-Ld	p=0.983	included:
n=2471 (no	Cemetery	10.8 ± 1.9		Alt>P'ment	p<0.001		Br-Rd	p=0.102	χ^2 = 69.23,
outliers)	Garden	12.8 ± 1.6		Alt>Verge	p<0.001		Ed-Ld	p=0.910	p<0.0001
	Manmade surface	0.4 ± 0.2		Cem>MMS	p<0.001		Ed-Rd	p=0.601	
	Nature reserve	5.3 ± 1.2	Outliers included:	Cem>OGS	p<0.031 §		Ld-Rd	p=0.227	
	OGS (outliers)	12.0 ± 8.9	χ^2 = 76.00, p< 0.0001	Cem>P'ment	p<0.001				
	OGS (no outliers)	4.2 ± 1.2		Cem>Verge	p<0.001	Outliers included:	Br-Ed	p=0.976	Outliers included:
	Park	6.0 ± 0.9		Gdn>MMS	p=0.005	χ^2 = 3.76, p=0.290	Br-Ld	p=0.986	χ^2 = 68.91,
	Pavement	0.4 ± 0.1		Gdn>P'ment	p<0.001		Br-Rd	p=0.254	p<0.0001
	Verge	3.3 ± 0.5		Gdn>Verge	p=0.002		Ed-Ld	p=1.000	
				NR>MMS	p=0.013		Ed-Rd	p=0.487	
				OGS>MMS	(p=0.078) †		Ld-Rd	p=0.443	
				Park>MMS	p=0.002				
				NR>P'ment	p<0.001				
				OGS>P'ment	p<0.001				
				Park>P'ment	p<0.001				
				Park>Verge	p=0.004				
				NR>Vrg	(p=0.087)				
				Verge>P'mnt	p=0.005				
Hoverflies	Allotment	8.9 ± 1.4	χ^2 = 54.11, p< 0.0001	Alt>MMS	p=0.025	χ^2 = 21.65, p<0.0001	Br-Ed	p<0.001	χ^2 = 47.70,
n=1078	Cemetery	3.7 ± 0.9		Alt>OGS	p<0.001		Br-Ld	p=0.994	p<0.0001
	Garden	6.3 ± 0.7		Alt>P'ment	p<0.001		Br-Rd	p=0.028	
	Manmade surface	0.3 ± 0.2		Alt>Verge	p<0.001		Ed-Ld	p<0.001	
	Nature reserve	2.4 ± 0.6		Cem>P'ment	p<0.001		Ed-Rd	p=0.576	
	Other greenspace	1.3 ± 0.3		Cem>Verge	p= 0.012		Ld-Rd	p=0.014	
	Park	2.6 ± 0.6		Gdn>OGS	p= 0.049				
	Pavement	0.3 ± 0.1		Gdn>P'ment	p<0.001				
	Verge	1.3 ± 0.3		Gdn>Verge	p<0.001				
				NR>P'ment	p=0.002				
				NR>Verge	(p=0.060)				
				Park>P'ment	p<0.001				
				Park>Verge	p=0.021				
Non-syrphid	Allotment	9.9 ± 3.1	χ^2 = 75.83, p< 0.0001	Alt>MMS	p=0.009	χ^2 = 5.48, p=0.140	Br-Ed	p=0.723	χ^2 = 39.26,
Diptera	Cemetery	7.2 ± 1.9		Alt>P'ment	p<0.001		Br-Ld	p=0.876	p<0.0001
n=1373	Garden	6.5 ± 1.3		Alt>Vrg	p=0.010		Br-Rd	p=0.554	
	Manmade surface	0.03 ±0.03		Cem>MMS	p=0.005		Ed-Ld	p=0.292	
	Nature reserve	2.9 ± 0.8		Cem>P'ment	p<0.001		Ed-Rd	(p=0.079)	
	Other greenspace	2.9 ± 1.0		Cem>Verge	p<0.001		Ld-Rd	p=0.945	
	Park	3.4 ± 0.5		Gdn>MMS	p=0.030				
	Pavement	0.1 ± 0.1		Gdn>P'ment	p<0.001				
	Verge	2.0 ± 0.3		NR>MMS	p=0.025				
				NR>P'ment	p<0.001				

				OGS>MMS	p=0.045				
				OGS>P’ment	p<0.001				
				Park>MMS	p=0.017				
				Park>P’ment	p<0.001				
				Park>Vrg	(p=0.095)				
				Verge>P’mnt	p=0.005				
Hymenoptera	Allotment	15.6 ± 1.9	χ^2 = 78.63, p< 0.0001	Alt>Cem	p<0.01	χ^2 = 33.16, p<0.0001	Br-Ed	p<0.001	χ^2 = 128.46,
n=1656	Cemetery	2.3 ± 0.6		Alt>MMS	p<0.01		Br-Ld	p=0.808	p<0.0001
	Garden	12.9 ± 1.4		Alt>NR	p=0.023		Br-Rd	(p=0.086)	
	Manmade surface	0.3 ± 0.2		Alt>OGS	p<0.01		Ed-Ld	p<0.001	
	Nature reserve	3.4 ± 1.0		Alt>Park	p<0.01		Ed-Rd	p<0.001	
	Other greenspace	1.2 ± 0.4		Alt>P’ment	p<0.01		Ld-Rd	p=0.471	
	Park	3.2 ± 0.7		Alt>Verge	p<0.01				
	Pavement	0.8 ± 0.3		Gdn>Cem	p<0.01				
	Verge	1.8 ± 0.4		Gdn>MMS	p=0.028				
				Gdn>OGS	p< 0.01				
				Gdn>P’ment	p=0.030				
				Gdn>Verge	p<0.01				
				NR>Cem	p= 0.041				
				NR>OGS	p<0.01				
				NR>Verge	p=0.019				
				Park>OGS	p=0.026				
				Park>Verge	(p= 0.080)				
Bees	Allotment	15.5 ± 1.9	χ^2 = 85.61, p< 0.0001	Alt>Cem	p< 0.01	χ^2 = 37.59, p<0.0001	Br-Ed	p<0.001	χ^2 = 129.20,
n=1579	Cemetery	2.1 ± 0.6		Alt>MMS	p< 0.01		Br-Ld	p=0.957	p<0.0001
	Garden	12.8 ± 1.4		Alt>NR	p< 0.01		Br-Rd	(p=0.090)	
	Manmade surface	0.3 ± 0.2		Alt>OGS	p< 0.01		Ed-Ld	p<0.001	
	Nature reserve	2.8 ± 0.9		Alt>Park	p< 0.01		Ed-Rd	p<0.001	
	Other greenspace	1.1 ± 0.4		Alt>P’ment	p< 0.01		Ld-Rd	p=0.272	
	Park	2.7 ± 0.7		Alt>Verge	p< 0.01				
	Pavement	0.8 ± 0.3		Gdn>Cem	p< 0.01				
	Verge	1.7 ± 0.4		Gdn>MMS	p=0.042				
				Gdn>OGS	p< 0.01				
				Gdn>Park	p=0.0416				
				Gdn>P’ment	(p=0.064)				
				Gdn>Verge	p< 0.01				
				NR>OGS	(p= 0.055)				
				NR>Verge	(p= 0.075)				
				Park>OGS	(p= 0.096)				

Supplementary Table 4. Results of GLMMs fitted with a binomial distribution testing for differences in presence/absence of different bee groups between the nine urban land uses

Significant pairwise Tukey *post hoc* comparisons are shown with all other pairwise comparisons non-significant ($p > 0.05$). Near-significant p-values are shown in brackets. Means and standard errors are calculated from the raw data. Alt: allotment, Cem: cemeteries, churchyards & burial grounds, Gdn: garden, MMS: manmade surface, NR: nature reserve, OGS: other green space, P'ment: pavement. The significance of the other main effects (city and floral abundance) are included in the table. Tukey *post hoc* comparisons are shown for pairwise city comparisons. Br: Bristol, Rd: Reading, Ld: Leeds, Ed: Edinburgh.

Taxon and sample size	Land use	Mean ± 1SE	Effect of land use (df=8)	Comparison	Tukey *post hoc* tests	Effect of City (df=3)	Comparison	Tukey *post hoc* tests	Effect of floral abundance (df=1)
Bumble bees	Allotment	10.9 ± 1.4	χ^2 = 35.96, p<0.0001	Alt>Cem	p=0.019	χ^2 = 17.94, p=0.0005	Br-Ed	p<0.001	χ^2 = 55.91,
n=983	Cemetery	1.0 ± 0.3		Alt>OGS	(p=0.062)		Br-Ld	p=0.809	p<0.0001
	Garden	7.1 ± 1.1		Alt>Park	(p=0.076)		Br-Rd	p=0.531	
	Manmade surface	0.2 ± 0.1		Alt>Verge	p=0.034		Ed-Ld	p=0.005	
	Nature reserve	1.7 ± 0.5		Gdn>Cem	p=0.023		Ed-Rd	p=0.013	
	Other greenspace	0.8 ± 0.4		Gdn>Verge	(p= 0.052)		Ld-Rd	p=0.966	
	Park	1.6 ± 0.5							
	Pavement	0.5 ± 0.2							
	Verge	1.0 ± 0.3							
Solitary bees	Allotment	1.4 ± 0.3	χ^2 = 50.80, p<0.0001	Alt>OGS	p<0.01	χ^2 = 31.13, p<0.0001	Br-Ed	p<0.001	χ^2 = 19.15,
n=218	Cemetery	0.7 ± 0.2		Alt>Verge	p=0.018		Br-Ld	(p=0.069)	p<0.0001
	Garden	2.0 ± 0.3		Gdn>NR	(p=0.090)		Br-Rd	p=0.539	
	Manmade surface	0.1 ± 0.03		Gdn>OGS	p<0.01		Ed-Ld	p=0.002	
	Nature reserve	0.3 ± 0.1		Gdn>Verge	p<0.01		Ed-Rd	p<0.001	
	Other greenspace	0.1 ± 0.1					Ld-Rd	p=0.652	
	Park	0.4 ± 0.1							
	Pavement	0.2 ± 0.1							
	Verge	0.3 ± 0.1							
Honey bees	Allotment	3.1 ± 0.9	χ^2 =35.89, p<0.0001	Alt>Cem	p<0.01	χ^2 =25.39, p<0.0001	Br-Ed	p<0.001	χ^2 =23.01,
n=378	Cemetery	0.4 ± 0.2		Alt>OGS	p=0.043		Br-Ld	(p=0.067)	p<0.0001
	Garden	3.7 ± 0.9		Alt>Verge	p<0.01		Br-Rd	p=0.998	
	Manmade surface	0.1 ± 0.1		Gdn>Cem	p<0.01		Ed-Ld	p=0.062	
	Nature reserve	0.9 ± 0.4		Gdn>OGS	p=0.037		Ed-Rd	p<0.001	
	Other greenspace	0.2 ± 0.1		Gdn>Verge	p<0.01		Ld-Rd	p=0.102	
	Park	0.7 ± 0.3							
	Pavement	0.2 ± 0.1							
	Verge	0.4 ± 0.2							

Supplementary Table 5. Results of GLMMs fitted with a Poisson distribution testing for differences in pollinator species richness between the nine urban land uses for all pollinator taxa, Diptera, hoverflies, non-syrphid Diptera, Hymenoptera, bees, bumble bees, solitary bees. Significant pairwise Tukey *post hoc* comparisons are shown with all other pairwise comparisons non-significant ($p > 0.05$). Near-significant p-values are shown in brackets. Means and standard errors are calculated from the raw data. Alt: allotment, Cem: cemeteries, churchyards & burial grounds, Gdn: garden, MMS: manmade surface, NR: nature reserve, OGS: other green space, P'ment: pavement. The significance of the other main effects (city and floral abundance) are included in the table. Tukey *post hoc* comparisons are shown for pairwise city comparisons. Br: Bristol, Rd: Reading, Ld: Leeds, Ed: Edinburgh.

Taxon and sample size	**Land use**	**Mean ± 1SE**	**Effect of land use (df=8)**	**Comparison**	**Tukey *post hoc* tests**	**Effect of City (df=3)**	**Comparison**	**Tukey *post hoc* tests**	**Effect of floral abundance (df=1)**
All taxa	Allotment	14.4 ± 1.1	χ^2 = 32.65, p<0.0001	Cem>MMS	p=0.018	χ^2 = 27.06, p<0.0001	Br-Ed	p<0.001	χ^2 = 21.60,
n=4996	Cemetery	7.8 ± 0.9		Cem>P'ment	p=0.019		Br-Ld	p=0.937	p<0.0001
	Garden	13.6 ± 0.7		Gdn>MMS	p=0.049		Br-Rd	p=0.411	
	Manmade surface	0.5 ± 0.2		Gdn>P'ment	(p=0.066)		Ed-Ld	p<0.001	
	Nature reserve	5.9 ± 0.9		NR>MMS	(p=0.083)		Ed-Rd	p<0.001	
	Other greenspace	3.5 ± 0.4		Park>MMS	p=0.015		Ld-Rd	p=0.798	
	Park	6.3 ± 0.7		Park>P'ment	p=0.015				
	Pavement	1.0 ± 0.2							
	Verge	3.9 ± 0.5							
Diptera	Allotment	7.7 ± 0.8	χ^2 = 44.78, p<0.0001	Alt>MMS	p=0.056	χ^2 = 15.69, p=0.001	Br-Ed	p=0.167	χ^2 = 14.76,
n=2952	Cemetery	5.7 ± 0.7		Alt>P'ment	p=0.037		Br-Ld	p=0.436	p=0.0001
	Garden	7.5 ± 0.5		Cem>MMS	p<0.01		Br-Rd	p=0.344	
	Manmade surface	0.2 ± 0.1		Cem>P'ment	p<0.01		Ed-Ld	p=0.003	
	Nature reserve	3.1 ± 0.6		Gdn>MMS	p=0.012		Ed-Rd	p=0.002	
	Other greenspace	2.6 ± 0.4		Gdn>P'ment	p<0.01		Ld-Rd	p=0.996	
	Park	4.2 ± 0.5		NR>MMS	p=0.022				
	Pavement	0.3 ± 0.1		NR>P'ment	p=0.011				
	Verge	2.7 ± 0.4		OGS>MMS	p=0.031				
				OGS>P'ment	p=0.018				
				Park>MMS	p<0.01				
				Park>P'ment	p<0.01				
				Verge>P'ment	p=0.011				
				Verge>MMS	p=0.024				

Hoverflies	Allotment	4.3 ± 0.5	χ^2 = 12.67, p=0.12	No sig difs	All ns	χ^2 = 3.05, p=0.385	Br-Ed	p=0.521	χ^2 = 10.95,
n=1078	Cemetery	2.2 ± 0.4					Br-Ld	p=1.000	p=0.0009
	Garden	4.1 ± 0.3					Br-Rd	p=0.981	
	Manmade surface	0.2 ± 0.1					Ed-Ld	p=0.578	
	Nature reserve	1.4 ± 0.3					Ed-Rd	p=0.354	
	Other greenspace	1.0 ± 0.2					Ld-Rd	p=0.979	
	Park	1.7 ± 0.3							
	Pavement	0.3 ± 0.1							
	Verge	1.1 ± 0.2							
Non-syrphid	Allotment	3.4 ± 0.4	χ^2 = 58.61, p<0.0001	Alt>P'ment	p=0.020	χ^2 = 6.84, p=0.077	Br-Ed	p=0.999	χ^2 = 9.84, p=0.002
Diptera	Cemetery	3.4 ± 0.6		Cem>MMS	(p=0.053)		Br-Ld	p=0.732	
n=1373	Garden	3.4 ± 0.3		Cem>P'ment	p=0.003		Br-Rd	p=0.128	
	Manmade surface	0.03± 0.03		Gdn>MMS	(p=0.076)		Ed-Ld	p=0.629	
	Nature reserve	1.7 ± 0.3		Gdn>P'ment	p=0.007		Ed-Rd	p=0.063	
	Other greenspace	1.6 ± 0.3		NR>MMS	(p=0.087)		Ld-Rd	p=0.701	
	Park	2.5 ± 0.4		NR>P'ment	p=0.009				
	Pavement	0.1 ± 0.04		OGS>P'ment	p=0.011				
	Verge	1.6 ± 0.2		Park>MMS	p=0.045				
				Park>P'ment	p=0.002				
				Verge>P'ment	p=0.010				
				Verge>MMS	(p=0.089)				
Hymenoptera	Allotment	5.3 ± 0.5	χ^2 = 7.77, p=0.46	No sig difs	All ns	χ^2 = 11.67, p=0.009	Br-Ed	(p=0.070)	χ^2 = 11.50,
n=1656	Cemetery	1.6 ± 0.4					Br-Ld	p=0.913	p=0.0007
	Garden	5.4 ± 0.4					Br-Rd	p=0.761	
	Manmade surface	0.3 ± 0.1					Ed-Ld	p=0.280	
	Nature reserve	1.8 ± 0.3					Ed-Rd	p=0.005	
	Other greenspace	0.7 ± 0.2					Ld-Rd	p=0.424	
	Park	1.6 ± 0.3							
	Pavement	0.6 ± 0.2							
	Verge	1.0 ± 0.2							
Bees	Allotment	5.1 ± 0.5	χ^2 = 6.76, p= 0.56	No sig difs	All ns	χ^2 = 11.85, p=0.008	Br-Ed	(p=0.071)	χ^2 = 10.12,
n=1579	Cemetery	1.4 ± 0.4					Br-Ld	p=0.922	p=0.001
	Garden	5.2 ± 0.4					Br-Rd	p=0.750	
	Manmade surface	0.2 ± 0.1					Ed-Ld	p=0.255	
	Nature reserve	1.5 ± 0.3					Ed-Rd	p=0.005	
	Other greenspace	0.7 ± 0.2					Ld-Rd	p=0.432	
	Park	1.5 ± 0.3							
	Pavement	0.7 ± 0.2							
	Verge	1.0 ± 0.2							

Bumble bees n=983	Allotment	3.1 ± 0.3	χ^2 = 8.29, p=0.41	No sig difs	All ns	χ^2 = 9.86, p=0.020	Br-Ed	(p=0.074)	χ^2 = 11.92, p=0.0006
	Cemetery	0.7 ± 0.2					Br-Ld	p=0.971	
	Garden	3.0 ± 0.3					Br-Rd	p=0.912	
	Manmade surface	0.1 ± 0.1					Ed-Ld	p=0.232	
	Nature reserve	1.0 ± 0.2					Ed-Rd	p=0.016	
	Other greenspace	0.5 ± 0.1					Ld-Rd	p=0.719	
	Park	0.9 ± 0.2							
	Pavement	0.4 ± 0.1							
	Verge	0.6 ± 0.1							
Solitary bees n=218	Allotment	1.3 ± 0.3	χ^2 = 7.17, p=0.52	No sig difs	All ns	χ^2 = 3.41, p=0.333	Br-Ed	p=0.541	χ^2 = 0.72, p=0.398
	Cemetery	0.6 ± 0.2					Br-Ld	p=0.886	
	Garden	1.6 ± 0.2					Br-Rd	p=0.985	
	Manmade surface	0.1 ± 0.03					Ed-Ld	p=0.284	
	Nature reserve	0.3 ± 0.1					Ed-Rd	p=0.645	
	Other greenspace	0.1 ± 0.04					Ld-Rd	p=0.771	
	Park	0.3 ± 0.1							
	Pavement	0.2 ± 0.1							
	Verge	0.2 ± 0.1							

Supplementary Table 6. Results of GLMMs fitted with a negative binomial distribution testing for differences in floral abundance and richness between the nine urban land uses **a.** floral abundance for all plants, native and non-native plants; **b.** floral richness for all plants, native and non-native plants, df=8 for all models. Significant pairwise Tukey *post hoc* comparisons are shown with all other pairwise comparisons non-significant (p > 0.05). Near-significant p-values are shown in brackets. Means and standard errors are calculated from the raw data. Alt: allotment, Cem: cemeteries, churchyards & burial grounds, Gdn: garden, MMS: manmade surface, NR: nature reserve, OGS: other green space, P'ment: pavement.

Supplementary Table 6a

Plant group	Land use	Mean ± 1SE	Effect of land use	Comparison	Tukey *post hoc* tests
All plants	Allotment	2525.3 ± 372.9	χ^2 = 129.20, p< 0.0001	Alt>Cem	p=0.019
	Cemetery	854.2 ± 131.6		Alt>MMS	p< 0.001
	Garden	2834.6 ± 370.8		Alt>NR	p=0.009
	Manmade surface	82.0 ± 40.2		Alt>OGS	p=0.022
	Nature reserve	1036.0 ± 366.8		Alt>Pk	p=0.001
	OGS	1214.5 ± 573.1		Alt>P'ment	p< 0.001
	Park	712.2 ± 119.0		Alt>Verge	p=0.030
	Pavement	233.0 ± 77.9		Cem>MMS	p< 0.001
	Verge	891.6 ± 135.9		Cem>P'ment	p< 0.001
				Gdn>Cem	p=0.003
				Gdn>MMS	p< 0.001
				Gdn>NR	p=0.002
				Gdn>OGS	p=0.005
				Gdn>Park	p< 0.001
				Gdn>P'ment	p< 0.001
				Gdn>Verge	p=0.005
				NR>MMS	p< 0.001
				NR>P'ment	p=0.001
				Park>MMS	p< 0.001
				Park>P'ment	p=0.004
				P'ment>MMS	p=0.013
				OGS>MMS	p< 0.001
				OGS>Pvt	p< 0.001
				Verge>MMS	p< 0.001
				Verge>P'ment	p< 0.001
Native plants	Allotment	811.4 ± 103.9	χ^2 = 104.81, p< 0.0001	Alt>MMS	p< 0.001
	Cemetery	800.3 ± 130.7		Alt>P'ment	p< 0.001
	Garden	943.1 ± 161.9		Cem>MMS	p< 0.001
	Manmade surface	30.9 ± 18.1		Cem>P'ment	p< 0.001
	Nature reserve	999.6 ± 366.0		Gdn>MMS	p< 0.001
	Other greenspace	1199.4 ± 573.3		Gdn>P'ment	p< 0.001
	Park	667.5 ± 117.7		NR>MMS	p< 0.001
	Pavement	142.6 ± 76.0		NR>P'ment	p< 0.001
	Verge	826.7 ± 135.1		Park>MMS	p< 0.001
				Park>P'ment	p< 0.001
				P'ment>MMS	p=0.006
				OGS>MMS	p< 0.001
				OGS>Pvt	p< 0.001
				Verge>MMS	p< 0.001
				Verge>P'ment	p< 0.001
Non-native plants	Allotment	1680.9 ± 325.5	χ^2 = 154.85, p< 0.0001	Alt>Cem	p< 0.01
	Cemetery	53.9 ± 20.2		Alt>MMS	p< 0.01
	Garden	1848.3 ± 341.2		Alt>NR	p< 0.01
	Manmade surface	51.1 ± 30.3		Alt>OGS	p< 0.01
	Nature reserve	36.4 ± 17.8		Alt>Pk	p< 0.01
	Other greenspace	13.6 ± 6.4		Alt>P'ment	p< 0.01

	Park	44.6 ± 30.4		Alt>Verge	p< 0.01
	Pavement	90.4 ± 22.7		Cem>OGS	p=0.033
	Verge	63.1 ± 22.8		Gdn>Cem	p< 0.01
				Gdn>MMS	p< 0.01
				Gdn>NR	p< 0.01
				Gdn>OGS	p< 0.01
				Gdn>Park	p< 0.01
				Gdn>P'ment	p< 0.01
				Gdn>Verge	p< 0.01
				OGS>Pvt	p< 0.01

Supplementary Table 6b

Plant group	Land use	Mean ± 1SE	Effect of land use	Comparison	Tukey *post hoc* tests
All plants	Allotment	32.3 ± 1.7	$\chi^2 = 166.36$, $p< 0.0001$	Alt>Cem	p< 0.01
	Cemetery	13.0 ± 1.0		Alt>MMS	p< 0.01
	Garden	38.6 ± 2.0		Alt>NR	p< 0.01
	Manmade surface	1.6 ± 0.4		Alt>OGS	p< 0.01
	Nature reserve	7.9 ± 0.9		Alt>Pk	p< 0.01
	OGS	7.6 ± 0.7		Alt>P'ment	p< 0.01
	Park	8.9 ± 0.8		Alt>Verge	p< 0.01
	Pavement	5.6 ± 0.8		Cem>MMS	p< 0.01
	Verge	10.9 ± 0.8		Cem>NR	p=0.044
				Cem>OGS	p< 0.01
				Gdn>Cem	p< 0.01
				Gdn>MMS	p< 0.01
				Gdn>NR	p< 0.01
				Gdn>OGS	p< 0.01
				Gdn>Park	p< 0.01
				Gdn>P'ment	p< 0.01
				Gdn>Verge	p< 0.01
				NR>MMS	p=0.022
				Park>MMS	p=0.010
				P'ment>MMS	p< 0.01
				OGS>MMS	(p=0.077)
				Verge>MMS	p< 0.01
Native plants	Allotment	15.8 ± 0.8	$\chi^2 = 63.44$, $p< 0.0001$	Alt>MMS	p< 0.01
	Cemetery	11.6 ± 0.9		Alt>NR	p=0.030
	Garden	15.9 ± 0.8		Alt>OGS	p< 0.01
	Manmade surface	1.1 ± 0.3		Alt>P'ment	p< 0.01
	Nature reserve	7.2 ± 0.8		Cem>MMS	p< 0.01
	Other greenspace	6.9 ± 0.6		Cem>NR	p=0.043
	Park	8.2 ± 0.7		Cem>OGS	p< 0.01
	Pavement	3.5 ± 0.5		Cem>P'ment	p< 0.01
	Verge	9.7 ± 0.7		Gdn>MMS	p< 0.01
				Gdn>OGS	p=0.014
				Gdn>P'ment	p< 0.01
				NR>MMS	p< 0.01
				NR>P'ment	(p=0.053)
				Park>MMS	p< 0.01
				Park>P'ment	p< 0.01
				OGS>MMS	p< 0.01
				Verge>MMS	p< 0.01
				Verge>P'ment	p< 0.01
Non-native plants	Allotment	16.0 ± 1.2	$\chi^2 = 329.1$, $p< 0.0001$	Alt>Cem	p< 0.001
	Cemetery	1.5 ± 0.2		Alt>MMS	p< 0.001
	Garden	22.4 ± 1.6		Alt>NR	p< 0.001
	Manmade surface	0.5 ± 0.1		Alt>OGS	p< 0.001
	Nature reserve	0.6 ± 0.2		Alt>Pk	p< 0.001

Other greenspace	0.7 ± 0.2	Alt>P'ment	$p < 0.001$
Park	0.6 ± 0.1	Alt>Verge	$p < 0.001$
Pavement	2.1 ± 0.3	Cem>Park	($p = 0.088$)
Verge	1.1 ± 0.2	Cem>Pvt	$p < 0.001$
		Gdn>Alt	$p = 0.043$
		Gdn>Cem	$p < 0.001$
		Gdn>MMS	$p < 0.001$
		Gdn>NR	$p < 0.001$
		Gdn>OGS	$p < 0.001$
		Gdn>Park	$p < 0.001$
		Gdn>P'ment	$p < 0.001$
		Gdn>Verge	$p < 0.001$
		NR>P'ment	$p < 0.001$
		P'ment>MMS	($p = 0.059$)
		P'ment>OGS	$p < 0.001$
		P'ment>Park	$p < 0.001$
		P'ment>Verge	$p < 0.001$

Supplementary Table 9. Robustness increase per additional 100,000 m^2 (10 hectares) associated with area increases of 25%, 50% and 75%

	Bristol			Edinburgh			Leeds			Reading		
	Area increase			Area increase			Area increase			Area increase		
	25%	50%	75%	25%	50%	75%	25%	50%	75%	25%	50%	75%
Allotment	0.203	0.159	0.126	0.297	0.233	0.185	0.389	0.309	0.248	0.118	0.092	0.072
Cemetery	0.066	0.051	0.040	0.150	0.112	0.085	0.063	0.050	0.039	0.138	0.103	0.077
Garden	0.014	0.011	0.008	0.017	0.013	0.011	0.023	0.018	0.014	0.018	0.014	0.011
Manmade surface	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Nature reserve	0.055	0.041	0.032	0.028	0.021	0.016	0.069	0.050	0.037	0.022	0.016	0.012
Other greenspace	0.001	0.001	0.001	0.003	0.003	0.002	0.002	0.002	0.002	0.002	0.002	0.001
Park	0.012	0.010	0.008	0.016	0.013	0.010	0.022	0.018	0.015	0.016	0.013	0.010
Pavement	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	0.001	0.001
Verge	0.023	0.018	0.015	0.009	0.007	0.006	0.007	0.005	0.004	0.014	0.011	0.009

Supplementary Table 10. Site selection approach for selecting sampling sites for each of the nine land uses in each of the ten regions per city

Details on site selection methods for each land use. Sites too small to locate a 100 m transect or for which permission could not be obtained to sample were excluded from selection.

Land use	Site selection	Site requirements
Allotment	One site selected at random per region. If no accessible site in a region, the closest available site in an adjacent region was sampled.	Large enough to locate a 100 m transect, permission to sample granted from site manager.
Cemetery	One site selected at random per region. If no accessible site in a region, the closest available site in an adjacent region was sampled.	Large enough to locate a 100 m transect, permission to sample granted from site manager.
Garden	See Supplementary Methods for details.	Individual gardens selected for sampling had to be at least 5 m by 5 m in size to accommodate transects.
Manmade surface	Random point selected using ArcGIS and closest suitable site selected.	Large enough to locate a 100 m transect, permission to sample granted by appropriate authority.
Nature reserve	One site selected at random per region. If no accessible site in a region, the closest available site in an adjacent region was sampled.	Large enough to locate a 100 m transect, permission to sample granted from site manager.
Park	One site selected at random per region.	Large enough to locate a 100 m transect, permission to sample granted by council.
Other greenspace	Random point selected using ArcGIS and closest suitable site selected.	Large enough to locate a 100 m transect, permission to sample granted by appropriate authority.
Pavement	Random point selected using ArcGIS and closest suitable site selected.	Pavements at least 2 m wide. If grass verges comprised part of the 2 m pavement width the site was not used for sampling.
Road verge	Random point selected using ArcGIS and closest suitable site selected.	Verge must be a minimum of 2 m wide and at least 100 m long. Verges adjacent to busy roads and all roundabouts were excluded from sampling for safety reasons.

Supplementary Table 11. Transect selection methods for each of the nine land uses

Details on how transects were located within each land use. More detailed information on how garden sites were selected is given in the Supplementary Methods.

Land use	Transect selection method	Transect route constraints
Allotment	Random point selected within the site on a map. Transect start point located as close to random point as possible. Direction of transect from start point randomly selected.	Route constrained to run along plot edges to avoid trampling planted vegetables and flowers in plots. Sampling included vegetation in allotment plots, grass paths and boundary vegetation.
Cemetery	Random point selected within the site on a map. Transect start point located as close to random point as possible. Direction of transect from start point randomly selected.	Transects did not cross graves and avoided new burial sites. Cut flowers were not included in sampling.
Garden	Two 5 m transects were used in each garden. One transect was located along a garden edge and the other in the central part of the garden to ensure the range of habitats within gardens was sampled (i.e. both flower bed and lawn). The start point of the edge transect was chosen by selecting a corner of the garden at random. The start point of the central transect was chosen at random. Edge and central transects were positioned so they did not overlap.	Sheds, greenhouses and ponds were not sampled and transects routed to avoid these features.
Manmade surface	Transect start point was located as close as possible to random point used to select the site (see Supplementary Table 10).	Transects were walked in a random direction from the start point, although re-routed where necessary to ensure a safe route.
Nature reserve	Main habitats[†] present at site mapped and approximate areas at site estimated by mapping in Google Earth. The total transect distance (100 m) was split proportionally between all habitats present at a site. The start point for each transect segment in each habitat was selected at random and transect direction from start point selected at random.	Transects were redirected around impenetrable scrub.
Pavement	Transect start point was located as close as possible to random point used to select the site (see Supplementary Table 10).	Any flowers overhanging the transect width were sampled (including street trees and overhanging vegetation from nearby gardens). Verges were not including in sampling, as these are counted as a separate land use.
Park	Identical selection method to nature reserves	Hard surfaces (including play areas and paths) excluded from sampling.
Other greenspace	Identical selection method to nature reserves	Hard surfaces (including play areas and paths) excluded from sampling.
Road verge	Transect start point was located as close as possible to random point used to select the site (see Supplementary Table 10). Transects were located at least 2 m from busy roads.	If verge not continuous, non-grass sections not included in the transect.

[†] Habitats mapped: improved grassland, broad-leaved woodland, rough grassland, other grassland, heathland, mixed woodland

Supplementary Table 12. Floral unit definitions

How 'floral units' were defined for all plant taxa sampled in the study.

Floral Unit definition	**Plant taxa**
Single flower	*Acanthus mollis, Acer* spp.*, Alstroemeria* spp., all Amaranthaceae, all Amaryllidaceae, all Asparagaceae, *Begonia* spp., *Camellia japonica*, *Centaurium erythraea*, *Cuphea ignea*, *Cyclamen hederifolium*, *Berberis* spp., all Boraginaceae, all Brassicaceae (apart from *Lobularia maritima*), all Campanulaceae, all Caprifoliaceae (apart from *Sambucus nigra*), all Caryophyllaceae, *Chenopodium* spp., all Cistaceae, all Convolvulaceae, all Crassulaceae, all Cucurbitaceae, *Dipsacus fullonum*, *Dorotheanthus bellidiformis*, all Ericaceae (apart from *Calluna vulgaris*), *Escallonia* spp., *Euonymus* spp., all Fabaceae (apart from *Medicago* spp. and *Trifolium* spp.), *Francoa sonchifolia*, all Geraniaceae, *Hamamelis* sp., *Hedera helix*, *Houttuynia cordata*, all Hydrangaceae, *Hypericum* spp., *Ilex* spp., *Impatiens* spp., all Iridaceae, *Kniphofia* sp., all Lamiaceae (apart from *Lavandula* spp.), *Hemerocallis* spp., *Limnanthes douglasii*, all Liliaceae, *Linum grandiflorum*, all Malvaceae, *Magnolia* sp., *Mercurialis perennis*, all Montiaceae, *Myrtus communis*, *Nemophila menziesii*, all Oleaceae (apart from *Syringa* sp.)**,** all Onagraceae, *Odontites vernus*, *Oxalis* spp., *Pachysandra terminalis*, *Paeonia* sp., all Papaveraceae, *Passiflora caerulea*, *Plantago* spp., all Polemoniaceae, all Polygonaceae (apart from *Persicaria bistorta*, all Plumbaginaceae, all Primulaceae, all Ranunculaceae, *Reseda luteola*, *Ribes* spp., all Rosaceae (apart from *Spiraea* spp.), all Rubiaceae, all Rutaceae, all Saxifragaceae, all Scrophulariaceae (apart from *Buddleja* spp., *Veronica* spp. (subgenus *Pseudoveronica*)), all Solanaceae, *Streptocarpus* sp., *Tamus communis*, *Tilia* spp., *Tropaeolum* spp., *Valerianella* spp., *Veratrum nigrum*, all Verbenaceae, *Vinca* spp., *Viola* spp., *Zantedeschia* spp.
Single capitulum	All Asteraceae (except *Solidago canadensis* and *Solidago gigantea*), Dipsacaceae (apart from *Dipsacus fullonum*)
Single branch of capitula	*Solidago canadensis*, *Solidago gigantea*
Part of panicle	All *Spiraea* spp.
Secondary umbel	All Apiaceae
Single catkin	All *Salix* spp.
Single compound cyme	*Centranthus ruber*
Single corymb	*Cornus* spp., *Sambucus nigra*
Single cyme	*Euphorbia* spp. (apart from *Mercurialis perennis*)
Single panicle	*Buddleja* spp., *Syringa* sp.
Single raceme	*Calluna vulgaris*, *Lobularia maritima, Medicago* spp., *Persicaria bistorta*, *Trifolium* spp., *Veronica* spp. (subgenus *Pseudoveronica*)
Single spadix	*Arum maculatum*
Single spike	*Lavandula* spp.
Single thyrsi	*Ceanothus* spp.

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